

The University of Chicago

Geology of the Stonington Region, Connecticut

A Dissertation
Submitted to the Faculty
of the Ogden Graduate School of Science
in candidacy for the degree of
Doctor of Philosophy

DEPARTMENT OF GEOLOGY

By
LAURA HATCH MARTIN

Bulletin No. 33
Connecticut Geological and Natural History Survey
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The Geology of the Stonington Region, Connecticut

By
LAURA HATCH MARTIN, Ph.D.

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PREFACE

This bulletin presents the results of a detailed study of the geology of the region about Stonington, Connecticut, and in part is based on a manuscript on "The Physical Geography and Geology of the Region around Westerly, Rhode Island", presented at the University of Chicago in partial fulfillment of the requirements for the degree of doctor of philosophy. The field work occupied fourteen weeks during the summers of 1913, 1914 and 1915, and ten weeks in the summer of 1921, with minor revisions in the areal mapping in 1922 as the result of field work on the New London quadrangle which adjoins the Stonington quadrangle on the west. The petrographic study of collected material was done under Professor Albert Johannsen of the University of Chicago and Professor Charles Berkey of Columbia University. The writer wishes to express her grateful acknowledgment to Professors Johannsen and Berkey for much helpful criticism, and also to the late Professor R. D. Salisbury and Dr. R. T. Chamberlin for assistance in connection with the glacial and structural problems.

THE GEOLOGY OF THE STONINGTON REGION, CONNECTICUT

By LAURA HATCH MARTIN

The region treated in this report is situated in the extreme southeastern part of Connecticut and the adjacent southwestern part of Rhode Island and is bounded on the south by Block Island and Fishers Island Sounds. It embraces an area of about 110 square miles lying within the Stonington topographic atlas sheet, as shown in Fig. 1.

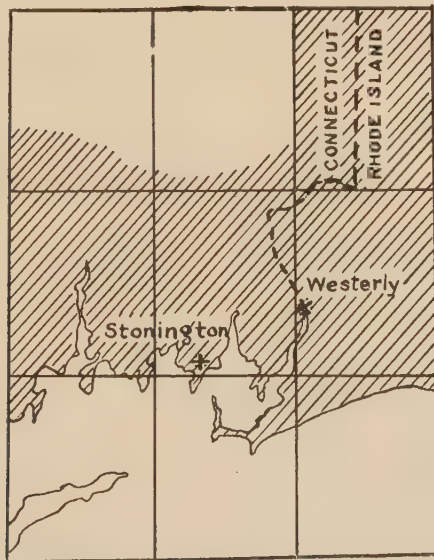


FIGURE 1. Map of Stonington quadrangle showing extent of Stonington region. The unshaded portion in the upper left hand corner was covered by Dr. G. F. Loughlin in his studies published in U. S. Geological Survey Bulletin, 492, 1912.

GEOGRAPHY

The northern part of the area is a region of hills composed either of bare rock, or rock thinly mantled with till. The elevation of the highest hills is slightly over 500 feet. Many of the hills are notably flat topped, regardless of the character of the underlying rock, and appear to be remnants of a former erosion surface of low relief. The general slope of the region is to the south, and the relief, which is from 300 to 400 feet at the north, diminishes gradually until it is not more than 20 to 40 feet near the shore. (See Fig. 2). A strip of country about a mile wide extending eastward along the coast from Watch Hill has the hilly topography of a typical terminal moraine. This moraine is in line with Fishers Island and is a continuation of the inner—Harbor Hill—moraine of Long Island.

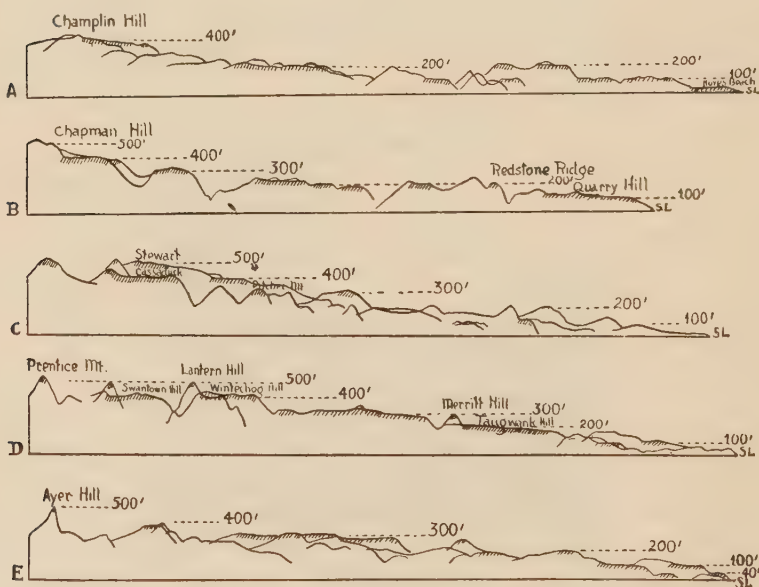


FIGURE 2. Profiles of hills and divides in the Stonington quadrangle.

The region is drained by a number of streams of which the only important ones are the Pawcatuck and Mystic. The drainage on the whole is poor; swamps are common and salt marshes and ponds fringe the coast and extend for a mile or two inland. Nor-



mally the drainage is to the south, but for that portion behind the terminal moraine the circuitous course of the Pawcatuck offers the only outlet.

The difference in the coastline east and west of the mouth of Pawcatuck River is very striking. West of the river rocky headlands, embayments, and off-shore islands predominate, while to the east, beaches of sand extend almost unbrokenly, behind which are shallow tidal lagoons.

GEOLOGY.

The region is underlain by igneous and metamorphic rocks which comprise: (1) a series of ancient schists; (2) a grano-diorite of variant character, the Stonington gneiss; (3) a series of granitic intrusions known as the Sterling granite gneiss; (4) a series of parallel east-west dikes of granite or quartz-monzonite; (5) veins of aplite, pegmatite, and quartz; (6) dikes of diabase. The rocks in the first three groups, and most of those included in group five, have been usually classed as pre-Cambrian, but recent studies point to a Pennsylvanian age for most of the granites. The unconsolidated deposits consist of till and stratified drift. In spite of the drift cover, however, bedrock outcrops throughout most of the region are plentiful and well suited for study.

PREVIOUS WORK

Previous to this investigation, little detailed work had been done on the geology of the region. Of reports relating to Connecticut, those by Mather¹, Shepard², and Percival³ were published so long ago that they are now mainly of historical interest. More recent reports by Rice and Gregory⁴, by Gregory and Robinson⁵, and by Barrell and Loughlin⁶ contain brief descriptions of the rocks and other geological features. Dale⁷ has described in detail the chief

¹ W. W. Mather, Sketch of the geology and mineralogy of New London and Windham counties in Connecticut. 1834. See also, Amer. Jour. Sci., 1st. ser., vol. 23, p. 404, 1833.

² C. U. Shepard, A report on the Geological Survey of Connecticut. 1837.

³ J. C. Percival, Report on the geology of Connecticut. 1842.

⁴ W. N. Rice and H. E. Gregory, Manual of the Geology of Connecticut. Conn. Geol. and Nat. Hist. Survey, Bull. 6, 1906.

⁵ H. E. Gregory and H. H. Robinson, Preliminary geologic map of Connecticut. Conn. Geol. and Nat. Hist. Survey, Bull. 7, 1907.

⁶ J. Barrell and G. F. Loughlin, The lithology of Connecticut. Conn. Geol. and Nat. Hist. Survey, Bull. 13, 1910.

⁷ T. N. Dale, The chief granites of Massachusetts, New Hampshire, and Rhode Island. U. S. Geol. Survey, Bull. 354, 1908, and also, with H. E. Gregory, The granites of Connecticut. Bull. 484, 1911.

quarries in the vicinity of Westerly and all points of economic importance concerning the coarse Redstone granite and the fine-grained, or monumental, granites. In 1912, the results of the first detailed mapping of a part of southeastern Connecticut, the Preston region, were published by Loughlin¹, the area studied by him adjoining on the northwest that treated in this report. The work of Davis² and of Barrell³ on the physiographic history of southern New England has a direct bearing on the interpretation of the geology of the Stonington region, and the glacial studies of Fuller⁴ furnish a basis for a comparison of the Pleistocene geology with that of Long Island.

THE ANCIENT SCHIST SERIES

AREAL DISTRIBUTION

The ancient schist series extends over about one-third of the region, the location of the known parts being shown on the geologic map facing page 12. It probably underlies, also, a large part of the swampy area back of the terminal moraine, as the schist is less resistant than the igneous rocks and lies at lower levels, except where strengthened by numerous granitic sheets. Near the northern border of the schist area granitic injection is very marked in places, as along the upper course of Mystic River, and has much changed the original character of the rock, thus making it difficult to draw an exact boundary. It was particularly difficult to place the boundary where the Sterling granite, normally of reddish color, becomes gray, at the locality two miles north-northwest of Old Mystic. As the scale of the geologic map is not sufficiently large to permit showing these injection zones, it has been necessary to draw the boundary as a single line, located where the schist and granitic injections appeared to be equal in amount.

Small masses of the ancient schists are also found surrounded by granite and grano-diorite. In the Sterling granite they are

¹ G. F. Loughlin, The gabbros and associated rocks at Preston, Connecticut. U. S. Geol. Survey, Bull. 492, 1912.

² W. M. Davis, The physical geography of southern New England. Nat. Geog. Soc., Mon. I, pp. 269-304, 1895.

³ J. Barrell, Piedmont terraces of the northern Appalachians and their mode of origin. Bull. Geol. Soc. Amer., 4th ser., vol. 24, pp. 688-690 (abstract), 1913. Also, The piedmont terraces of the northern Appalachians. Amer. Jour. Sci., 4th ser., vol. 49, pp. 227-258, 327-362, 407-428, 1920. The latter paper was published after Prof. Barrell's death and was edited by H. H. Robinson.

⁴ M. L. Fuller, Geology of Fishers Island. Bull. Geol. Soc. Amer., vol. 16, pp. 367-390, 1905. Also, Geology of Long Island. U. S. Geol. Survey, Prof. Paper 82, 1914.

generally inconspicuous, but in the grano-diorite—Stonington gneiss—area it is rare to find any considerable outcrop of the igneous rock which does not include one or more schist masses. Few of these masses, however, are large enough to be shown on the geologic map.

CHARACTER OF THE SERIES

The following members make up the greater part of the series: (1) quartz-biotite schist; (2) quartzite; (3) hornblende and other amphibolite schists; (4) feldspathic schists of probable sedimentary origin.

Quartz-biotite schist constitutes the main body of the series. It occurs in nearly every exposure but in such similar relations, whether above or below another member, that it is impossible to assign definite horizons to the separate beds. It is commonly found alternating with quartzite bands, but in many places quartzite is absent; the amphibolite and feldspathic members also occur in the same interbedded relations.

Quartzite is common within the series, occurring in thin layers. It is always impure, containing biotite in thin flakes, or hornblende, and grades along the strike, as well as across it, into quartz-biotite or amphibolite schist. The quartzite does not occur in the massive form and relative purity that it does farther north and west.

Hornblende schist is abundant and occurs in different associations within the series. The thin layers, interstratified with the quartz-biotite schist and with the impure quartzite, are undoubtedly of sedimentary origin. On the other hand there are hornblende schists which occur in such thick beds of uniform appearance as to suggest an igneous origin.

Feldspathic beds are an important component of the series at some localities. Some of them most probably are recrystallized arkose deposits, but others are highly granitized schists. As already noted, granitization of the schists is a rather common phenomenon in this region, making it difficult to say in many instances, without very detailed study, whether certain rocks should be considered sedimentary or igneous.

The series as a whole is dark colored, but in places alternating thin layers of black hornblendic schists, green schists, and quartzite produce a striking banded effect, and facilitate weathering

of the beds into thin slabs. Very commonly minute crenulations and numerous injections mask the structure of the rocks (Plate 1, a). Where the strata are not intricately folded, however, the bedding planes are generally observable; and even where contortion is pronounced, the bedding is presumably shown by the layers of different minerals, such as the fine bands of variant composition in the green schists, the layers of kinzigite, and other metamorphosed products. In every case the schistosity corresponds with the bedding, even to the minute contortions. The weaker layers have accommodated themselves to the stronger and give the appearance of having flowed in a plastic mass.

These ancient schists of the Stonington region correspond to those which have been mapped elsewhere in southeastern Connecticut as Putnam gneiss and Plainfield quartz schist, and have been traced northward into Massachusetts¹. These two formations have been studied in detail by Dr. Loughlin in the Preston region which adjoins the Stonington region on the northwest².

HISTORY.

The detailed history of the schist series cannot be told because definite horizon markers are lacking and the rocks have been intensely folded and highly metamorphosed. The latter conditions indicate, however, that the sediments were buried under great load and then subjected to mountain making stresses. The period of most intense folding, during which the rocks acquired their schistose structure, occurred before, or perhaps contemporaneously with, the intrusion of the Stonington gneiss—the oldest igneous rock of the region. There was, however, some folding of a later date, for different degrees of contortion in the schists are associated with the successive igneous injections (Plate V, b). All these deformations must have occurred when the rocks were in the zone of flow.

A second period of dynamic action took place after prolonged erosion had greatly reduced the overlying load of sediments and brought those remaining into the zone of fracture. At this time faulting and jointing of the rocks occurred. Some of the displace-

¹ W. N. Rice and H. E. Gregory, *Manual of the Geology of Connecticut*. Conn. Geol. and Nat. Hist. Survey, Bull. 6, pp. 129-134, 1906.

² G. F. Loughlin, *The gabbros and associated rocks at Preston, Connecticut*. U. S. Geol. Survey, Bull. 492, p. 16, 1912.

ment zones were later filled with granite or pegmatite and these rocks have also been slightly faulted, thus indicating that there was another, though minor, period of dynamic action.

PETROGRAPHY OF THE SCHIST SERIES.

The more common varieties of the schists, as they occur in the adjacent Preston region, have been already described¹, and only those will be treated here which throw additional light on the origin of the series. In particular, the relations of the thin quartzite layers to the interbedded gray, green, and black schists have been little studied. They are valuable, however, as determining the sedimentary origin of otherwise doubtful beds.

Interbedded quartzite and green schist.

At several localities in the region, quartzite in layers an inch or two in thickness grades into, and is also interbedded with, a green schist. In some instances, fine layers of biotite schist and kinzigite are also present. This relationship is best seen one-half mile west of Ashaway, where the beds are extremely contorted. Megascopically, the green layers consist of a white granular mass with well-orientated flakes of a light green ferro-magnesian mineral and a little biotite.

Under the microscope, the faintly greenish color of the rock is seen to be due to the presence of actinolite crystals, which have a subparallel arrangement. The rock contains about 25 per cent. of this mineral, and, in addition, xenomorphic granular diopside (35 per cent.), quartz (20 per cent.), small grains of andesine filled with sausserite (10 per cent.), and microcline (8 per cent.). Titanite and zircon are accessories, and calcite is the chief secondary product. The field relations and peculiar composition of this rock, with calcium, magnesium, and low alumina, indicate the recrystallization of an impure limestone.

Interbedded quartzite and quartz-biotite schist

This rock is strikingly banded, the black and white layers ranging from one-sixteenth to one-half inch in thickness. Some of the black bands are pure biotite, others pure hornblende, and still

¹ G. F. Loughlin, loc. cit., pp. 16-21.

others contain more or less quartz with both biotite and hornblende. Where the quartzite bands are associated primarily with quartz-biotite schist bands, the rock has the following microscopic character. The quartzite layer, which is typical of the embedded quartzite layers of the series, has a groundmass of xenomorphic quartz and andesine grains, averaging 1 mm. in diameter, in which very small well orientated biotite laths and a few apatite grains are embedded. Some of the dark layers consist chiefly of large biotite crystals, contain more feldspar than quartz, and include many accessory and secondary minerals. The chief minerals in the biotite schist are quartz, andesine, biotite, and hornblende; as accessories are zoisite, epidote, monazite, titanite and zircon. Secondary mica is more highly developed in the plagioclase of the biotitic bands. Some bands have a higher percentage of hornblende, and the rock may pass abruptly into a typical hornblende schist. The schist shows the effects of strain since its recrystallization.

The interbedding of biotite schist with quartzite undoubtedly indicates sedimentary origin, but in the present recrystallized product there is no indication of the original grains of the sediment. The biotite schist probably represents original clayey layers with a high calcium content. The iron and magnesium of the biotite, however, may be due to included basic sediment or to the addition of such elements to calcareous layers from adjacent igneous rocks, as seems to be the case for some of the amphibolite schists. Some of the accessory minerals (monazite and zircon) may have been inherited from igneous rocks from which the sedimentary material was derived.

Interbedded quartzite and hornblende schist.

The interbedding of quartzite with the hornblende schist is most interesting. At some localities the layers of these two rocks are remarkably distinct; at others they clearly grade into each other. The alternating beds for the most part are one-half to one inch thick, although some are less than one-sixteenth inch.

Under the microscope the quartzite shows xenomorphic granular quartz (75 per cent.), andesine intergrown with the quartz and including some minute crystals of titanite, biotite, and apatite (15 per cent.), hornblende (7 per cent.), and biotite (3 per cent.).

The larger grains of quartz and feldspar are generally elongated in the same direction as the biotite and hornblende crystals. Some andesine crystals are almost completely altered to white mica and the biotite is partly chloritized.

The hornblende schist interbedded with the quartzite consists of the same minerals but in very different proportions. Quartz is practically absent (only about two per cent.), whereas hornblende comprises 53 per cent., and andesine 45 per cent., of the rock. Titanite and magnetite are important accessories.

Hornblende schist

The hornblende schist described in this section occurs in thick massive layers or lenses in the schist series, with no relation to the quartzite. The uniform grain throughout any one exposure is particularly noticeable, although at some localities it is coarse, having a dioritic effect, whereas at others, it is fine or almost aphanitic.

Under the microscope the rock is found to be mainly hornblende (60 per cent.), and andesine or labradorite (30 per cent.). The feldspar is commonly untwinned. The schistosity is apparent in the general parallel orientation of the hornblende. Biotite is present in very small quantity. Magnetite and hematite form about six per cent. of the rock, the former in great abundance and generally surrounded by titanite. The usual small apatite and zircon grains are present. Quartz is never present except in small amount, and is generally absent. The character, composition, and field relations of many of the massive hornblende schist layers associated with the quartz-biotite schist, and of some thin layers associated with quartzite, suggest that the original material was basaltic tuff and without doubt was deposited in water. The origin of the extensive hornblende schist formation of the Preston region was similarly explained by Loughlin¹.

It seems probable, however, that other masses of hornblende schist represent original calcareous and dolomitic material. The nearest recognizable deposits of such material are found in North Stonington, and Loughlin describes a specimen from the contact of dolomite and hornblende schist in which bands rich in tremolite alternate with those rich in green hornblende. The actinolite, tremolite, and epidote patches and layers occasionally found in the

¹ Loc. cit., pp. 19 and 66-67.

schists of the Stonington region probably indicate the former presence of lenses of impure limestone.

Adams and Barlow¹ concluded that the amphibolites in the Haliburton and Bancroft areas in Canada were derived from limestones because they found transition members between unaltered limestone at a distance from the batholiths of that region and amphibolites, without calcite, near them. Their general conclusion was that "under intense metamorphism a number of rock types, very different in origin and character, yield a convergent type of alteration products which belong to the class of amphibolites and which resemble one another so closely that they are in many cases indistinguishable."

Greater metamorphism in the Westerly region than farther north in Connecticut and east in Rhode Island, where limestones have been reported, may account not only for the lack of calcareous layers but also for the lack of phyllites and slates, and instead the development of gray biotite schists and feldspathic gneisses.

There are other masses of hornblende schist of coarse grain and cross-cutting relations, as well as a few injections in the feldspathic gneisses retaining parallel walls, which are undoubtedly igneous intrusions. Locally this massive type is indistinguishable from the Stonington gneiss, a gneissoid quartz-diorite in the southwestern part of the region which is clearly igneous and later than the quartzite and sedimentary hornblende schists.

Meta-conglomerate

The quartz-biotite schist contains a thin layer of meta-conglomerate, one mile west of Ashaway. The latter is additional proof, therefore, of the sedimentary origin of the schist, and is important for correlation purposes.

The matrix of the meta-conglomerate is grayish in color and similar to the schist in composition. The pebbles are represented by elongate patches of white very schistose material, averaging three-fourths of an inch in length, one-fourth of an inch in width, and one-sixteenth of an inch in thickness.

The difference between the pebble and the matrix is very apparent under the microscope. The pebble shows a decidedly

¹ F. D. Adams and A. E. Barlow. Geology of the Haliburton and Bancroft Areas, Ontario. Geol. Survey of Canada, Dept. of Mines, Memoir 6, 1910.

schistose structure and consists of quartz (80 per cent.), and sillimanite (19 per cent.), with garnet, muscovite and an apatite forming the remaining 1 per cent. The sillimanite fibers (Plate II, a.) are developed chiefly between elongated six-sided quartz grains. The matrix, on the other hand, shows a general rough orientation of biotite crystals (about 15 per cent.), without notable elongation of the associated quartz. Oligoclase-andesine occurs in small amount (five per cent.), and sillimanite is absent. The accessory minerals are much the same as in the pebbles. The matrix shows the effects of strain. The composition of the matrix seems to indicate an original sandy mud, whereas the pebbles were derived from an argillaceous sandstone free from iron and the alkaline bases.

Meta-conglomerates from Wordens Pond and Watsons Pier, R. I.

For the purpose of determining the extent of the schist series in neighboring regions, and also of determining the age of the schists in the Stonington region, the meta-conglomerates at Wordens Pond, R. I., six miles east of Westerly, and at Watsons Pier, on Narragansett Bay, were studied.

In the hand specimen the rock from Wordens Pond closely resembles the meta-conglomerate which occurs at Ashaway. The pebbles have the same appearance, but in general are somewhat larger, and the matrix is the same biotite schist. Under the microscope the rock is seen to be practically identical in texture and mineral composition with the Ashaway meta-conglomerate. The pebbles are the same sillimanite schist and the matrix is the same biotite schist, except that the oligoclase-andesine is present in somewhat greater amount (10 per cent.) (Plate II, b.). It may be said, therefore, that the meta-conglomerate of the Stonington region extends as far east as Wordens Pond, or but six miles from the west side of Narragansett Bay.

At Watsons Pier on the west shore of Narragansett Bay, the Kingston series of Pennsylvanian age is exposed and has a very schistose character. In places this series develops a phase which somewhat resembles the Ashaway and Wordens Pond meta-conglomerates in general size of grain and in having small white patches which were formerly pebbles. The matrix is a biotite schist but has a peculiar bluish sheen, due to muscovite, which was not observed in the conglomerates from the other localities.

The microscopic structure, however, is very different from the two meta-conglomerates described above, and there is no sharp division between the pebbles and the matrix. The pebbles consist of pure quartz, which is strained, cracked, and intergrown around the edges with the quartz of the matrix. The pebbles vary in size from 1 cm. to about 1 mm. The larger ones are decidedly elongated, and in thin section show only a broad belt of cracked quartz, but the smaller ones keep their oval form and are not always completely orientated (see Q, Plate III, a.). The matrix consists of albite (about 60 per cent.), quartz (35 per cent.), biotite (four per cent.), and muscovite (one per cent.). Apatite in quite large grains and colorless garnet are also present in very small amount. Magnetite dust is present and gives rise to a part of the limonite stain, which is also due to the alteration of biotite. Zircon gives pleochroic halos in biotite.

This rock is apparently a recrystallized sediment consisting of quartz pebbles embedded in an arkosic matrix. The zircon was derived from some older igneous rock, whereas the large apatite crystals may show recrystallized phosphatic material of organic origin.

The rock at Watsons Pier thus differs radically from the meta-conglomerates at Ashaway and Wordens Pond. No sillimanite schist is present, the pebbles having come from quartz veins or pure quartzite rock. The matrix is not only finer grained and has an entirely different appearance, but is composed largely of albite, whereas the western conglomerates contain only small amounts of oligoclase-andesine.

AGE RELATIONS.

The sedimentary rocks of the Stonington region are so highly metamorphosed that no fossils remain. The only method of ascertaining their age is to trace them, or their associated igneous rocks, into regions where rocks of known age occur. The nearest area is the Narragansett Basin, where Carboniferous rocks are unconformable on a complex of ancient schists, rare Cambrian sediments, and intrusives, except on the southwest, where an irruptive contact occurs. Metamorphism has affected some of the Narragansett sediments, and the metamorphism increases in intensity

toward the southwest¹, the area with which this study is particularly concerned.

The ancient sedimentary series of the Stonington region outcrops in discontinuous bands or isolated masses in the granite, and cannot therefore be traced continuously to the Narragansett Basin. Large swamps and a heavy drift cover add to the difficulty.

It is possible, however, to trace the igneous rocks of the region into an area where sedimentary rocks of known age occur. G. F. Loughlin² has found that the Sterling batholith extends from the Stonington region to the southwest border of the Narragansett Basin, where it invades the Kingston series of Mid-Pennsylvanian age. He concludes that the ancient schists of the Preston region (which are continuous with those of the Stonington region) are the more highly metamorphosed equivalent of that series, and hence are Mid-Pennsylvanian in age.

The writer agrees with Dr. Loughlin that the schist series of Connecticut extends in the same relations to the granite as far east as Wordens Pond, the most convincing evidence being the exact similarity between the meta-conglomerate at Wordens Pond and that at Ashaway. (See Plate II, a, and b.). It appears more reasonable, however, to correlate this series with the ancient Blackstone series which is found in patches along the western border of the Narragansett Basin, and is overlain unconformably by the Kingston sediments.

It seems unlikely that sediments of Mid-Pennsylvanian age could have been laid down in the Stonington region, deeply buried, and subjected to strong folding and igneous injection before the main granite intrusion of the region occurred in late Pennsylvanian time. Although there is as great metamorphism in part of the Kingston sediments as in the schists in Connecticut, yet its origin is not so complex and can be attributed either to the heat and water of the intruding granite or to the contemporaneous diastrophic effects. Successive foldings preceding the Sterling granite, with igneous injections of variant composition,

¹ F. H. Lahee, Relations of the degree of metamorphism to geological structure and to acid intrusions in the Narragansett Basin, R. I. Amer. Jour. Sci., 4th ser., vol. 33, pp. 366-367, 1912.

² Intrusive granites and associated metamorphic sediments in southwestern Rhode Island. Amer. Jour. Sci., 4th ser., vol. 29, pp. 447-457, 1910. Also, with L. A. Hechlinger, An unconformity in the Narragansett Basin of Rhode Island and Massachusetts. Ditto, 4th ser., vol. 38, pp. 45-64, 1914.

are unknown in the Narragansett region so far as the writer has been able to ascertain.

The main reasons, therefore, for believing that the ancient schists of the Stonington region are not of the same age as the Kingston sediments, are: (1) the difference in general character of the two series, and (2) the likeness of the schists in the Stonington region to those of the ancient Blackstone series which form part of the complex on which the Kingston sediments were deposited.

The Kingston series, where not highly metamorphosed, consists of normal sedimentary rocks, predominantly impure sandstones and shales with some conglomerate in which the pebbles are quartzite. Carbonaceous matter is abundant, whereas limestone and basic matter, which could be recrystallized into hornblende schists, is practically absent. The Kingston series, although cut by sheets of the Sterling granite (Plate I, b.) around its southwestern border and by some basic igneous rocks in the northwest part of the basin, is not intimately associated with them, and is entirely free from them at a short distance from the border. The sedimentary character of the strata is clearly shown, even in the most highly metamorphosed beds, by the difference in composition and grain of the material and the gradation to phyllites, slates, and graphitic beds.

The Blackstone series, with which it is proposed to correlate the schists of the Stonington region, has been described by J. B. Woodworth¹, B. K. Emerson and J. H. Perry², and more recently by C. H. Warren and Sydney Powers³. It is an ancient schist series dominantly sedimentary, consisting of quartzites, quartzschists, phyllites, green schists and amphibolites, and thick beds of crystalline limestones with soapstone and serpentine. The series is cut by granite, and large areas of schist have thus been isolated, such as the quartzite area near Natick, Rhode Island. There were also earlier igneous intrusions some of which were basic.

Similarities between the Blackstone series and the schist series of the Stonington region are striking.

¹ (With N. S. Shaler and A. F. Foerste), The geology of the Narragansett Basin. U. S. Geol. Survey, Mon. 33, pp. 104-109, 1899.

² The green schists and associated granites and porphyries of Rhode Island. U. S. Geol. Survey, Bull. 311, p. 10, 1907.

³ Geology of the Diamond Hill, Cumberland district in Rhode Island and Massachusetts. Bull. Geol. Soc. Amer., Vol. 25, p. 440, 1914.

Quartzites occur in both but are much thicker in the Blackstone series. They are gray, brownish, or yellowish in color, due to minute included biotite flakes. The quartzites of both series grade into quartz-biotite schists and hornblende schists, but the Blackstone in addition has talc and serpentine intra-beds which seem to be lacking in the schists of the Stonington region. Similar green schists and amphibolites are common to the two series.

Both schist series have similar intimate relations to early igneous rocks; some of the latter cannot be separated easily from the sedimentary members of the series.

Both series show the effects of very intense dynamic action, with perhaps more faulting than folding in the Blackstone series as compared with the schists of the Stonington region, a difference which may be due to the greater extent and massiveness of the quartzites.

The distribution of the Blackstone series in "elongate patches which are enclosed in a great granite batholith on all sides up to the point where they are in contact with the Carboniferous"¹ is strikingly like the distribution of the schists in the Stonington region.

Most of the patches of the Blackstone series are mapped as occurring in Milford granite (of doubtful age), but one large area of schists south of Pascoag, R. I., called Marlboro and Westboro formations, is known to be enclosed in Sterling granite². It seems more reasonable to the writer to correlate the isolated patches in the same batholith with one another than with the sediments of a well defined basin of the Narragansett type. Furthermore, Emerson has mapped the Plainfield quartz schist in northeastern Connecticut with the Westboro ("Grafton") quartzite, and the Putnam gneiss adjacent to that formation on the west. If, therefore, a more detailed study of the Plainfield quartz schist and Putnam gneiss should show that their distribution is as given on the preliminary geologic map of Connecticut³, then the correctness of the proposed correlation of the ancient schists of the Stonington region with the Blackstone series would seem assured.

The exact age of the Blackstone series is not known. It is undoubtedly pre-Pennsylvanian because the Kingston series, at

¹ B. K. Emerson and J. H. Perry, loc. cit., p. 11.

² B. K. Emerson, *Geology of Massachusetts and Rhode Island*. U. S. Geol. Survey, Bull. 597, p. 26, 1917.

³ Conn. Geol. and Nat. Hist. Survey, Bull. 7, 1907.

several localities along the western side of the Narragansett Basin, contains pebbles derived from the Blackstone beds and from the granite which intrudes them¹. Emerson and Perry placed the Blackstone series in the Cambrian, because it seemed to have been derived from rocks similar to the Attleboro and Braintree Cambrian rocks. Loughlin also accepts the Cambrian age for the series. Most workers in this field, however, have placed the series in the pre-Cambrian².

THE IGNEOUS ROCKS.

The igneous rocks of the Stonington region are: (1) the Stonington gneiss, a gray grano-diorite of variant composition not before recognized as a separate formation; (2) the Sterling granite gneiss group, which includes several closely related rocks generally light pink to red in color; (3) blue and gray granite and quartz monzonite in dikes, known as the Westerly monumental granites; (4) aplites, pegmatites, and igneous quartz of several ages; (5) diabase in small dikes. The Preston gabbro, which is shown on the geologic map, has been described by Dr. G. F. Loughlin³, and hence is not treated in this report. The areal distribution of the foregoing groups of rocks is shown on the geologic map (facing page 12). Because of the intricate association of the different rocks, it is rare to find areas of any size where only a single type occurs. It should be kept in mind that subordinate amounts of other igneous rocks, and of schists, may be present in addition to the one indicated.

THE STONINGTON GNEISS.

The Stonington gneiss is the oldest igneous rock of the region because it is cut by all the others. It extends along the coast from the vicinity of Pawcatuck River westward to the border of the region. It is well exposed in a roughly circular area the center of which is about two and one-half miles northeast of Stonington. Within this area, injections of later granites are scarce, but there

¹ B. K. Emerson and J. H. Perry, loc. cit., p. 38. G. F. Loughlin, loc. cit., Amer. Jour. Sci., 4th ser., vol. 38, p. 51, 1914.

² W. O. Crosby, Contributions to the geology of eastern Massachusetts, Boston. Soc. Nat. Hist., Occas. Papers, No. 3, 1880. N. S. Shaler, On the geology of the Cambrian district of Bristol County, Mass. Harvard College, Mus. Comp. Zool., Bull., vol. 16, p. 15, 1888. J. B. Woodworth, loc. cit., p. 105. C. H. Warren and Sydney Powers, loc. cit., p. 445. B. K. Emerson, loc. cit., p. 26.

³ U. S. Geol. Survey, Bull. 492, 1912.

are numerous included masses of schist. Both east of the Pawcatuck and west of Stonington, however, the rock becomes much cut up and otherwise affected by later intrusions. The rock of these portions will be spoken of as the "Stonington mixture" and is indicated on the geologic map by an over-pattern placed on that of the Stonington gneiss. In the Stonington mixture one can generally see that the schists were disrupted first by the Stonington gneiss, the numerous schist blocks showing all stages of assimilation. Later the early phases of the Sterling granite intrusions in some places evidently softened the gneiss, so that the two rocks became thoroughly interleaved or mixed in a marble cake fashion. The succeeding injections of the Sterling, and still later granites, show an increasing definiteness of contact with the gneiss. Thus exposures of the Stonington mixture give an impression of disorder as compared with the distinctly banded injection gneiss to be described later.

Even within the roughly circular area of few injections, the Stonington gneiss shows a high degree of variability. The most striking variety is a very coarse quartz-diorite composed of andesine, hornblende, mica, and a very little quartz, showing flow structure and very little evidence of strain. This grades into a black and white gneiss, an oligoclase-granite, in which hornblende may or may not be present with the black biotite, and evidence of great strain is apparent. In places this variety becomes slightly pinkish in color, but this is rare, and the rock as a whole presents a gray, or black and white appearance. It is possible that many of the abrupt variations in composition are due to assimilation of the schists.

On the east the Pawcatuck marks the general boundary of the massive development of the gneiss. But the Stonington mixture extends a little farther east as shown by boulders and the few exposures under the till on Quarry Hill south of Westerly. In the southeastern part of the region outcrops are buried to large extent under glacial drift and swamps.

On the north and for a short distance on the southeast, the rock injects the schists parallel to their bedding and, becoming more and more compressed, is indistinguishable from the hornblende-plagioclase schists. This border zone is about one-half mile wide and is mapped as injection gneiss. The rock has a decidedly banded ap-

pearance, consisting as it does of black schists alternating with gray gneisses, and in places is cut by red granite or pegmatite sheets. This banded rock is in the same general alignment as the neighboring schists but differs notably from the much disturbed part of the Stonington gneiss (Stonington mixture), although both may show the same component members and may grade abruptly into each other along their contact.

PETROGRAPHY

The Stonington gneiss has a highly variable character but may be divided into its most typical phases: (1) quartz-diorite, (2) black and white oligoclase-granite, (3) pinkish phases intermediate in character between the above varieties and the Sterling injections.

Quartz-diorite

Megascopic characters. The quartz-diorite is a coarse-grained black and white rock with a strong flow structure. It consists chiefly of grayish-white plagioclase and hornblende. A little quartz is present and small amounts of biotite, magnetite, pyrite, and probably allanite.

Microscopic characters. The rock is coarse-grained and has a xenomorphic, inequigranular texture. Andesine crystals, three to four mm. in diameter, make up about 60 per cent. of the rock, while deep green hornblende (15 per cent.), quartz (13 per cent.), and biotite (five per cent.) are next in importance. Orthoclase (five per cent.) and accessories, chiefly magnetite, make up the remainder of the rock. The andesine is in well twinned crystals in places enclosed by large irregular hornblende grains. Magnetite forms grains two mm. in diameter. It is generally surrounded by titanite, and in places surrounds oval grains of monazite, an interesting mineral already reported from the Westerly region by Dr. Kemp¹. Zircon, apatite, and pyrite complete the list of accessory minerals. Allanite may be present, unless stains similar to those produced by it can be attributed to the monazite (Plate III, b.).

The rock is very little altered, and the plagioclase is especially fresh as compared with that of the members of the Sterling series.

¹ J. F. Kemp, Granites of southern Rhode Island and Connecticut, with observations on Atlantic Coast granites in general. Bull. Geol. Soc. Amer., vol. 10, p. 368, 1899.

Although a little kaolin and white mica is developed along some twinning bands, many large crystals of andesine may be found practically water-clear. Some of the biotite shows considerable alteration to chlorite and hematite.

There is little evidence of strain in the rock as a whole. The contacts between crystals are clear cut and there was evidently no movement after crystallization.

Within the quartz-diorite are found dark masses which seem to be clearly inclusions, yet are practically identical with the surrounding rock in composition, only more basic. In these the amount of andesine drops to 50 per cent., whereas the dark constituents increase. The iron ores make up about five per cent. of the rock and show an interesting interstitial character (Plate IV, a.).

There are also masses probably originally inclusions which show no traces of their original form or structure. These are the garnetiferous segregations, elongated in the direction of flowage, which are found in both the quartz-diorite (Plate V, a.) and the oligoclase-granite. The minerals have a somewhat concentric arrangement in places, the heavy hornblende and much of the plagioclase occupying the central portion, and the garnet with some epidote and andesine forming an outer zone in which there are occasional little threads of pyrite. From the composition of the minerals such segregations seem to be the result of the assimilation of lime-magnesian rocks by the hot magma.

Origin. The microscopic examination of the quartz-diorite and its included schist fragments upholds the hypothesis that the great variability of the rock is due to a large extent to the assimilation of many schist fragments, the whole association of rocks and inclusions showing a near roof condition.

The black and white oligoclase-granite

Megascopic characters. This phase is found over the greater part of the Stonington gneiss area and is especially well developed about a mile north of Stonington. The rock is medium to coarse grained, the mineral constituents being oriented in decided flow lines. Its general effect is a black and white gneiss which is much coarser than the other rocks of the region.

Microscopic characters. The rock is xenomorphic granular, the grains averaging about 1.2 mm. in diameter. It is composed of oligoclase (about 45 per cent.), quartz (30 per cent.), microcline and orthoclase (20 per cent.), biotite (four per cent.), and accessories (one per cent.). The accessories include titaniferous magnetite, some grains of which are surrounded by titanite rims, apatite, zircon, and either allanite or monazite in very small deep yellow grains causing a pleochroic halo in the biotite. Probably both are present.

In its lack of alteration it looks like the quartz-diorite phase already described. This type, however, shows more internal change due to pressure than any other non-recrystallized rock in the region.

Origin. The oligoclase-granite shows no special internal evidence of a complex history. Evidence of strain shows that it is one of the oldest rocks of the region. This is an important point, for the quartz-diorite into which it grades does not show this feature.

Pinkish intermediate phases

Under this head are grouped many parts of the Stonington gneiss which in general resemble the Sterling granite gneiss. Some of them (for example Pawcatuck Rocks, two miles south of Westerly,) are like the black and white oligoclase-granite just mentioned, only slightly red in color; others are clearly the result of injection of a later pinkish magma (alaskite or Redstone granite) into the gray or black and white Stonington gneiss. The pink Stonington gneiss as a rule is coarser than the normal granite gneiss and contains less biotite, which is less well distributed and orientated than in the latter. Hornblende is present with, or replaces, the biotite, and the rock has a fresh appearance contrasting with the great clouding of the feldspar which is characteristic of the Sterling granite gneiss. From a reddish weathered surface, however, it is often difficult to be certain whether Stonington gneiss or Sterling granite gneiss is present.

SUMMARY

The gradational contacts between the three types of Stonington gneiss show that they were probably all parts of the same magma. The quartz-diorite, being more locally developed than

the other phases, and more closely associated with inclusions, is probably a special phase which originally had the oligoclase-granite composition. The oligoclase-granite is not very different from the Sterling granite except in color, while the local pinkish phases closely resemble the latter on a weathered surface.

THE PROBLEM OF THE STONINGTON GNEISS

The Stonington gneiss is undoubtedly younger than the schists as it contains numerous inclusions of them and intrudes them along its northern and southeastern border. In the injection gneiss on the south side of Hinkley Hill, sheets of quartz-diorite occur which are quite gneissic in appearance and yet show the speckled appearance and microscopic characters of the Stonington gneiss. Traced farther north the quartz-diorite becomes less and less easily recognized, and either ceases or is indistinguishable from the coarse hornblende schists.

The more basic character of the Stonington gneiss as a whole, compared to the members of the Sterling granite series and its own occasional very basic character, suggests that it may be the upper part of an early local intrusion, similar to the gabbro laccolith of Preston, Conn., in which a lower more basic phase is covered, or that it may be an early igneous rock of considerable extent in neighboring regions, but represented here only in small quantity.

Various facts bear upon these hypotheses. Two features indicate that the Stonington gneiss may be an early local intrusion: (1) Its composition (quartz-diorite and oligoclase-granite), which is similar to the upper part of the Preston gabbro laccolith, and (2) the apparent curving of the structure lines at the contact with surrounding schists, a feature well shown by the attitude of the Redstone granite at the east end of Redstone Ridge. This suggests that by its intrusion the adjacent schists were oriented parallel with the periphery of the mass, whereas later granites coming from below were diverted to the border in much the same way as around the Preston gabbro ten miles farther north.¹

But the Stonington gneiss lacks the well defined boundary of the Preston laccolith, and the more basic part, a quartz-diorite, seems to have no determinable relation to the oligoclase-granite,

¹ G. F. Loughlin, U. S. Geol. Survey, Bull. 492, p. 32.

which here is in too great amount to be a local variation. Most of the Redstone granite is east and north of the Stonington gneiss, yet there are dikes of it, and also of alaskite, even in the heart of the area, so the gneiss did not divert the granite as a whole. The number of schist fragments included within the magma, as well as the alignment of the strikes and the verticality of the dips in those believed to be roof-pendants, show that the method of intrusion was probably by stoping rather than by the bending upward of overlying material. The fact that the quartz-diorite shows so little strain, and that so many of the schist fragments are angular, also disproves any suggestion that it might have been a sill or laccolith which was later so pressed that the schists of the roof were down-folded into the igneous rock, thus destroying the laccolithic form.

The change in the direction of the strike of the schists and granite sheets east of Westerly may have more to do with the Preston gabbro to the north than with the Stonington gneiss area. The prevailing strike of the schists and gneisses outside of the Stonington region is north-south¹, and it has been assumed by workers in the neighboring areas² that the general orogenic forces during the period in which the Sterling granite was injected, operated in a general east-west direction.

If the resistance set up by the Preston gabbro and added to by the force of the diverted granite sheets were sufficient to affect the schists five to ten miles from the border, then we would expect the east-west strikes parallel with the southern part of the gabro mass as seen in the belt along the Stonington gneiss border. The gradual weakening toward the east of the secondary forces set up by the gabbro until the structure of the rocks becomes controlled by the major east-west stress would account for the change in direction of the strike along the whole eastern border of the map. This seems to be corroborated on the New London map, for southwest of the gabbro mass the strikes again change to a north-south direction. Thus the Stonington gneiss is probably not a separate local intrusion similar to that of the Preston gabbro, nor does it seem to be related to the latter in any way.

It is probably more closely related to other igneous rocks noted

¹ Conn. Geol. and Nat. Hist. Survey, Bull. 7, Map.

² G. F. Loughlin, U. S. Geol. Survey, Bull. 492, pp. 30-32. Also, Amer. Jour. Sci. vol. 38, p. 57. A. C. Hawkins, Reconnaissance Map of R. I.

in adjacent parts of southern Connecticut. A similar gray variable gneiss has been described as part of the Mamacoke gneiss, and also as occurring near New London, Conn.¹

The Stonington gneiss, at least the highly injected phase, continues along the coast as far west as New London² and can probably be proved to be the same as the gray gneisses mentioned.

THE STERLING GRANITE GNEISS.

Sterling granite gneiss is the name given to a series of granite intrusions, many in the form of sheets, which cut all the older rocks of southeastern Connecticut and southwestern Rhode Island.

The Sterling granite has been called a gneiss, a term appropriate for most of the Sterling phases if a gneiss is a banded rock in which feldspar is important. If, however, a distinction is made between a gneissic and a gneissoid rock, meaning by the first, one in which a secondary structure has been developed by dynamic pressure, then the Sterling granites in the Stonington region are not true gneisses. They are gneissoid, or "flow granites", the orientation and banding of the constituents being a primary and not a secondary structure. The group name must necessarily be used rather loosely because one of the phases of the Sterling (Redstone granite) generally has no banding. Moreover, part of the series elsewhere seems to develop a true gneissic structure.³ Because of the great extent and general relations of the Sterling granite gneiss to older rocks, it is suggested that it is really a great batholithic mass, the roof of which has been removed in part only. As mapped by Loughlin⁴, the Sterling granite has a considerable development in the area which immediately adjoins the Stonington region on the north. It is also well developed in the region under discussion where it forms the northern boundary of the schist belt. It also breaks through the schists in numerous localities, the most notable exposure being found at the Redstone Ridge (Carrs Mountain) just north of Westerly. The Sterling granite also probably underlies the Stonington gneiss, for numerous dikes of its easily

¹ Manual of Geology of Connecticut. Conn. Geol. and Nat. Hist. Survey, Bull. 6, pp. 149 and 150, 1906.

² L. H. Martin, unpublished geologic map of New London quadrangle, east of Thames River.

³ U. S. Geol. Surv., Bull. 492, p. 120-126, 1912.

⁴ G. F. Loughlin, U. S. Geol. Surv., Bull. 492, Plate II, 1912.

recognizable phases (alaskite and Redstone), as well as red pegmatite, occur in most parts of the gray gneiss area.

The Sterling granite gneiss may be separated for convenience of description into three main varieties based on slight textural and compositional differences which by their structural relations show slightly different periods of intrusion. These are (1) granite gneiss, (2) alaskite, (3) Redstone granite.

THE GRANITE GNEISS.

The granite gneiss (similar to the "normal granite gneiss" described by Loughlin) is the phase of greatest development in the Stonington region. It is generally a pinkish or pinkish gray, fine-grained rock, and has a strongly developed primary orientation of the biotite crystals. On a fresh surface this feature is not very noticeable, but is brought out on weathered surfaces by depressions along the lines of the weaker minerals. It is somewhat variable in composition and grain and in places becomes lighter colored by the lessening of biotite content, so that there is difficulty in separating it from the alaskite. At some localities a greater development of pink feldspar crystals, which are arranged in wavy flow lines, suggests a porphyritic texture. The porphyritic, or augen, gneiss of the Preston region to the north is not recognized, however, within the Stonington region. The nearest approach to this rock is a coarse-grained granite, with a tendency to porphyritic development, found at Bradford, R. I., (just beyond the eastern border of the area) and for a mile southward.

The granite gneiss of this region is really a flow granite, although there is evidence of considerable strain in the undulatory extinction and cracking of the quartz and the occasional bending of the biotites, but the stresses were not sufficient to cause a true granulation or secondary orientation. The fact that the same rock, at least the porphyritic variety, farther north does show true gneissic structure, may mean that the period of injection was one of great dynamic action, as postulated by Loughlin, but that the pressure was either greater toward the north or that the rock intruded there solidified earlier. The granite farther south might still have remained plastic and would have had to conform to the different stresses by flowage and so bring about the strong flow lines developed in that section. Where the granite gneiss solidi-

fied before later material was injected, we have the predominance of the plagioclase feldspars as in the typical variety which has a composition of oligoclase (40 per cent.), quartz (30 per cent.), microcline (25 per cent.), and biotite (5 per cent.), but where injected by later granites a more acid, more inequigranular variety is found.

ALASKITE.

Alaskite, similar to that in the Preston region¹, occurs in the northern part of the area. It is light pink or tan in color, medium grained, and with a tendency to develop a gneissoid structure through the parallel orientation of the longer axes of the quartz and feldspar grains. It breaks through the schist in sheets and disrupting masses, as seen in the numerous exposures along Mystic River. It is also seen at the mouth of that river, and elsewhere, cutting the Stonington gneiss.

The intimate association of the alaskite with the material it injects is better seen in the Stonington gneiss area than elsewhere because of the contrasting colors of the rocks. In places there is a *lit-par-lit* injection on a small scale, each layer having the characteristic of the parent rock and yet grading into the other along the contact. A pseudoporphyritic variety is developed where the alaskite advanced along the flow lines of the gneiss or included schist and where the acid magma seems to have thoroughly permeated the older rock.

Alaskite injects the Sterling granite gneiss in the same way it does the Stonington gneiss. Within the parts mapped as alaskite and granite gneiss there is generally an interleaving of the two, and the geologic map simply shows the rock that is present in greatest abundance. In places the sheets seem to be quite thick and massive, but in practically every exposure some interleaved material can be found. In all cases the alaskite seems to have been injected during differentiation, for rocks transitional in composition between alaskite and the older Sterling granite gneiss can be found. Where typically developed, the rock is composed of about 53 per cent. microcline (and a little orthoclase), quartz (25 per cent.), albite (20 per cent.), biotite and muscovite (1 per cent.), ilmenite, and a little zircon. (Plate IV, b.)

¹ Loughlin, loc. cit., p. 123.

In the Stonington gneiss area the alaskite in places is pinker, and is interesting because here monazite occurs in large enough grains to be satisfactorily studied. The monzonite is associated with magnetite, but is in a group of crystals surrounding a few grains of the iron. The crystals are about 0.2 of a millimeter in diameter and are oval or rounded in outline. The aggregate covers an area one millimeter in length. Beautiful positive biaxial figures can be procured on basal sections, thus distinguishing it from xenotime. The latter gives a negative figure and was also found in a Westerly gray granite by Dr. Kemp.¹

THE REDSTONE GRANITE.

The main varieties of the Sterling granite have been described from neighboring regions, and the essential differences in their development in the Stonington area, already noted in this report. But Redstone granite has not before been separated as a distinct phase. This will therefore be discussed in detail.

The Redstone granite is the last distinct phase of the Sterling series. It resembles the granite gneiss in composition and was classed with it by Dr. Loughlin.² He notes that the "normal" granite gneiss shows less strain effect than the "porphyritic" granite gneiss farther north and states: "These characters are evidence that metamorphism diminished in amount to the southward. This rock at Westerly, R. I., three miles south of the area, is quarried under the name of Westerly Red granite."

The reasons for separating the Redstone (Westerly Red) granite from the normal granite gneiss are:

(1) The granite gneiss retains its characteristic gneissic appearance throughout its extent in the Stonington region. The whole type may be less gneissic than corresponding rocks in the northern part of the Preston area, but it does not grade into the non-gneissic Redstone as suggested by Loughlin.

(2) The Redstone granite is found not only in the Stonington region but cutting the Sterling granite gneiss at numerous places within the area mapped by Dr. Loughlin. However, the

¹ James F. Kemp. Intrusive granites of Rhode Island and Connecticut: Bull. Geol. Soc. Am., Vol. 10, pp. 368-9, 1899. Dr. Kemp found both monazite and xenotime in Westerly granites, and notes the fact brought out by Merrill in 1885 (Tenth Census, Vol. X, p. 20) that the Westerly granites in general are rich in accessory minerals.

² Loc. cit., p. 126.

abundant pegmatite, accompanying the Redstone granite, makes many contacts appear blurred.

(3) The Redstone granite has a typical granitic texture where developed in quantity, whereas the granite gneiss is a typical flow gneiss. The Redstone has been affected as much by dynamic action since its crystallization as the granite gneiss, and it also shows the same amount of strain in all parts of the region.

AREAL DISTRIBUTION

The Redstone granite is typically developed as thin sheets and small irregularly shaped intrusions throughout the granite gneiss areas, and where it breaks through the schists it is generally in sheets parallel with the structure. At Redstone Ridge, the red granite broadens from a few feet in thickness on the west to a mass half a mile wide near Westerly. From this point the granite continues east for two miles parallel with the schists, and then, with them, makes a sharp turn to the south. South of Burden (Chapman) Pond, the granite loses its sheet form but appears again farther east in a boss-like mass. Just what are the relations of the Redstone granite to the schists or other neighboring rock along the eastern border of the region cannot be told on account of the heavy drift and swamp deposits.

The Redstone granite cuts the Stonington gneiss as it does the Sterling granite gneiss to the north, and the boundaries are more clearly seen in the south because of the contrasting colors of the two rocks. The more general distribution of this Redstone variety, its coarse granitoid texture, and its broad boss-like development in the southeast corner of the region suggest that this granite may be the main batholithic material which underlies the region as a whole.

PETROGRAPHY

Megascopic characters. In its typical appearance the Redstone granite is a coarse-grained rock of medium red to greenish red color and much more massive than the other varieties of Sterling granite. The larger pink feldspar grains reach one-fourth to three-eighths inch in diameter, whereas the other grains average half that size. The rock consists of pink microcline, white to greenish plagioclase, quartz and biotite. Magnetite and pyrite are seen in most hand specimens, and rarely some rust producing crys-

tal, probably allanite. When in small quantities the granite is somewhat inequigranular. In places the rock grades into a biotite-pegmatite.

Microscopic characters. Where typically developed, as at a number of places on Redstone Ridge, the rock has a xenomorphic granular texture. In large dikes and sheets the estimated composition is: microcline and orthoclase (40 per cent.), oligoclase with oligoclase-albite rims (35 per cent.), quartz (20 per cent.), biotite (4 per cent.), and accessories (1 per cent.), while in smaller dikes and thin sheets the potash feldspars are greatly in excess, in places comprising 60 per cent. of the rock. The interior of the zonal plagioclase crystals is clouded with kaolin and sericite whereas the outer rim is clear, giving a clouded effect similar to that of the feldspar in the granite gneiss and in contrast to the clear plagioclase of the Stonington gneiss. The accessory minerals are more numerous but of the same kind as in the other Sterling phases. Secondary muscovite, in large irregular flakes, is associated with the feldspars, and is developed irregularly between minerals or fills cracks even in quartz grains.

Variations. The Redstone granite retains its typical character in almost every part of the region except where it grades into pegmatite or in the thinnest sheets where the biotite flakes are somewhat oriented. The only notable variation is that found at the west end of Morrisons Ridge, where the broad sheets of Redstone pinches out two miles north of Wequetequock. Here a coarse pinkish gray or white granite is found in which the quartz is in long parallel pencils or lenses. This variety can be traced eastward directly into the typical Redstone granite. The Redstone granite contains a few partly assimilated fragments of schists and the same biotitic knots and schlieren noted in the other varieties. Chlorite is developed along sheet jointing in a zone in the Redstone quarry. Near the joints the plagioclase feldspars also have become chloritized and the granite is unfit for use. Such zones are probably due to the shearing and pneumatolitic action accompanying the intrusion of diabase.

REDSTONE GRANITE IN NEIGHBORING REGIONS.

Samples of rock were taken at Narragansett Pier and at two miles west of Saunderstown, R. I., in the area mapped by Emer-

son and Perry as Northbridge gneiss, but considered by the writer as part of the Sterling batholith. The rock exposed at Narragansett Pier is indistinguishable from the Redstone both megascopically and microscopically, except that in places it is more pegmatitic and carries more muscovite. The "Northbridge gneiss" west of Saunderstown differs from the Redstone in some ways, but it is probably a border phase of the Sterling batholith. Its pencils of quartz resemble the local phase of Redstone on Morrisons Ridge (see above). It has a more acid composition, higher muscovite content, and greater strain conditions which can probably be explained by its closer contact with the sediments of the Narragansett Basin. Although it does not resemble the Redstone as closely as that at Narragansett Pier, it is probably the same thing, as more muscovitic phases of the latter were found north and west of Narragansett Pier grading into the "Northbridge gneiss".

THE WESTERLY MONUMENTAL GRANITES.

Fine-grained granites and quartz-monzonites cut the older igneous and metamorphic rocks as east-west dikes, which range in width from a few inches to 150 feet. In the broader ones quarrying has been carried on for a century and a half, and Westerly has become famous for its fine monumental stone.

Outcrops of this granite are most numerous in a zone two to three miles broad which passes almost due east and west through the town of Westerly, and includes all the commercial quarries from Mystic, Conn., to Bradford, R. I. One dike may be traced for a mile or more on the surface through the string of quarries at Bradford. The strike of the intrusions is somewhat irregular; in places the granite of the same dike appears to be separated by blocks of the country rock, or to wedge out completely. For these reasons it is impossible to predict whether good stone will be found along the strike as followed from the quarry.

The Westerly monumental granites are an entirely different series of intrusions from the Sterling granites, and can be easily distinguished from them by a finer grain, more massive structure, greater resistance to weathering, and by contact phenomena, such as the development of long biotite and radiating allanite crystals. They are prevailing east-west dikes with dips of 30 to 45 degrees to the south regardless of the changes in the strike and

sent transverse dikes of different material, because one at the Smith deep quarry seemed to contain oligoclase-andesine feldspar instead of the oligoclase to oligoclase-albite of the adjacent blue granite. This difference, however, does not seem important as the feldspars are so kaolinized and sericitized that they are very difficult of precise determination. There is no real line of demarcation between the good granite and the discolored, incoherent granite of the head wall. The transverse joints merely become more numerous, curved and intersecting, and the alteration of the granite becomes correspondingly greater. The joints are probably due to strain set up on cooling, groups of planes relieving the tension at fairly regular intervals. These then acted as avenues of escape for gases which altered the adjacent granite by pneumatolitic action, as is shown by the great amount of epidote, chlorite, sericite and hematite along the joint surfaces. That the head walls were originally the same material as the rest of the dike is shown by the presence of cores of unaltered blue granite in the center of the larger joint blocks. The deep pink color on the face of some of the vertical joints in other parts of the quarries is probably due to a similar deep-seated change which, however, did not go so far as to weaken the granite.

The monumental granites (quartz-monzonites and granodiorites) have been described by Dale¹. They may be divided into three types based on color. The blue (or gray) granite is in greatest abundance and makes up the bulk of the larger dikes, while pink or "swamp" granite is developed locally in the blue and in many of the smaller dikes, particularly those on the Redstone ridge. A third variety has a variable composition, pink or white color, and a greater length of biotite than the others. It is a contact phase in part at least. The relation of the granites to each other is an interesting petrographic problem.

WESTERLY BLUE (GRANODIORITE).

Westerly "blue" is a medium grained massive rock of blue to gray color, consisting of light greenish blue plagioclase feldspars, quartz, and biotite. Occasional grains of magnetite, titanite and a mineral producing brown stains may be seen in most hand specimens. The composition averages: oligoclase to oligoclase-albite

¹ Loc. cit.; also Bull. 484, 1911.

(45 per cent.), quartz (25 per cent.), microcline and orthoclase (22 per cent.), biotite (6 per cent.), accessories (2 per cent.) which include titanite in large crystals, magnetite, zircon, allanite (some twinned crystals), muscovite and apatite. This type is therefore a granodiorite.

The Westerly blue granodiorite is probably the original magma which intruded the older rocks, for it is in all of the larger dikes and is very uniform in appearance and composition throughout the region. Few strain effects are seen, showing that it was intruded after the reduction of the main stresses which affected the Sterling series.

WESTERLY PINK OR "SWAMP" GRANITE.

This rock is massive, very fine grained, pinkish-gray or buff in color, and highly esteemed for fine carving. It is like the "blue" in structure, but is more altered internally, the most striking difference being the greater clouding of the feldspar with pink kaolin, which apparently gives the color to the rock.

The composition of the rock is about the same as that of the blue granite. At the Pinkstone quarry a much more acid variety, quartz-monzonite, occurs, the composition of which is: quartz (40 per cent.), microcline (30 per cent.), oligoclase to oligoclase-albite (26 per cent.), biotite (2 per cent.). The accessories (2 per cent.) are magnetite, pyrite, zircon, apatite, allanite and augite (the latter in small isolated grains).

The difference in the color is probably due to some deep-seated change. At the Smith deep quarry, the place where the "blue" can be found grading into the pink or "swamp" granite, the sheets in the "swamp" are much thinner than elsewhere, and the vertical joints are also nearer together. Along these joints, also, the granite is a much deeper pink color, which suggests that whatever the change was, it was more intense along joint planes.

Contact phases. The monumental granites are generally associated with a pink or white phase in which the biotite crystals attain a size five and ten times that of the other grains. In most places the biotite is not in excessive amount but is conspicuous because needle like grains (in places three-eighths inch in length) are developed and roughly oriented into flow lines. This variety is conspicuous also in many places because the groups of radiating

allanite crystals have disappeared, leaving greenish brown stains in the rock.

This variety is the only one exposed in many places, as in the narrow dikes which intrude the injection gneiss on Talbot and Hinkley hills. It may be found along the upper contact of pink or blue granite dikes as at the Catto quarry where it is locally three feet thick.

A white or buff-colored variety with brown stains is found below the blue granite, at the Smith deep quarry at Westerly, and at Morrisons quarry two miles north of Wequetequock. Here the white granite is mixed with the blue in a marble cake fashion where the two come together, but the white also spreads up into the blue along vertical planes. The white is in considerable quantity in places, and is taken as a sign of the giving out of the blue granite in depth.

MINOR INJECTIONS.

Pegmatite and igneous quartz are associated with each of the periods of igneous intrusion but have small areal extent. The early pegmatites are mostly white or gray, whereas the later ones are uniformly pink. Aplite, of a deep pink color, is found cutting the monumental granite in narrow dikes, as at the Calder and Carnie quarry on the Redstone ridge, and is probably an end phase of the monumental granite stage of injection.

DIABASE DIKES.

Two narrow dikes of diabase cut the Redstone and the monumental granites at the Redstone quarry near Westerly.¹ They followed vertical undulating planes. The diabase is black in color and has well developed phenocrysts of olivine from one-sixteenth to one-twelfth inch in diameter. One dike is cracked parallel with its strike and filled with fibrous calcite or satinspar. There are also dark colored veins parallel with the dikes which cut the granite, and were probably made by hot emanations from below at a time immediately following the injection of the dike material.

Dale refers this diabase tentatively to the Triassic period to correspond with other Triassic dikes of neighboring regions. If

¹ T. Nelson Dale, U. S. Geol. Survey, Bull. 354, p. 281.

this may be assumed, a younger time limit is set for the granite intrusions, as these dikes cut the latest of the Sterling granite phases and the subsequent monumental granite as well.

AGE OF THE IGNEOUS ROCKS.

Dr. Loughlin was the first to trace the Sterling granite from the Westerly region to the Narragansett Basin.

At the contact with the sediments the granite is generally the porphyritic gneissoid variety, and it is associated with the Redstone granite which not only cuts it but invades the adjacent sediments.

On Tower Hill near Wakefield, R. I., Redstone granite carrying much muscovite is found injecting the sediments in irregular sheets. (Plate I, b). Along the shore near Watsons Pier, great white muscovite-bearing pegmatite dikes, possibly the equivalent of the Redstone granite, cut the highly inclined sedimentary rocks. These may be contemporaneous, however, with the still later intrusion of the monumental quartz-monzonite, for the latter is found cutting the Sterling granite near Wakefield and at Narragansett Pier in the same manner as in the Stonington region.

On all the contacts examined by the writer, Redstone granite and pegmatite were the only varieties of the Sterling series actually found cutting the sediments, but, as in every case they were also associated closely with the porphyritic gneissoid variety not far from the contact, it can be taken for granted that the batholith as a whole followed the laying down of the sediments.¹

The Redstone granite shows as much internal strain as the other Sterling varieties but no flow structure. Therefore if the flow structure was induced by pressure during intrusion, the Redstone granite must have come in after the granite gneiss had flowed and become partially solidified, but before the pressure on the region ceased. It is probably practically contemporaneous with the alaskite in the west, and grades into some of the pegmatites, at least, in the Narragansett Basin.

¹ The relation of the time of intrusion to the internal structure of the rock has been worked out petrographically by Dr. Loughlin for the Preston, Conn., region. (Loc. cit., pp. 127-133), and by Dr. Lahee for the Narragansett Basin (Loc. cit., p. 466). Both agree that the gneissoid structure was probably due to intrusion under stress, while the alaskite and the pegmatites were intruded when movement had practically ceased.

The sedimentary rocks in this portion of the Narragansett Basin are highly crystalline, but have been traced northward and found to be equivalent to the Coal Measures of Mid-Pennsylvanian age.¹ Thus the Redstone granite, at least, is post-middle Pennsylvanian. As the orogenic movement which folded the Kingston sediments is probably the same as that in which the granite gneiss was intruded, a post-Kingston age for the whole batholith, as assumed by Dr. Loughlin, seems reasonable. Dr. Loughlin² has also found that the Sterling batholith is pre-Dighton in age. He finds pebbles of both the porphyritic gneissoid (granite gneiss), and muscovitic (Redstone) varieties, as well as of the Kingston sediments, in the Dighton conglomerate in the northern part of the Basin. This calls for a great unconformity in the middle of the Narragansett series, or between the Kingston sediments which are Mid-Pennsylvanian, and the Dighton conglomerate which is Permian³ in age.

Thus all the petrographic evidence of dynamic pressure for the different stages of the Sterling granite must be related to the orogenic movement in late Pennsylvanian time rather than to that at the close of the Permian. The earlier movement was by far the greater, although the folding of the Dighton conglomerate "was sufficient to develop steeply dipping folds and intense compression effects; it" (from evidence in the Narragansett Basin) "was not accompanied by igneous intrusion."⁴ This second orogenic stage could not have extended much beyond the sides of the basins of sedimentation or the latter phases of the Sterling granite would show other effects than the slight strain in the quartz.

Dr. Loughlin concludes that the prevailing stress during the earlier movement was east-west, producing the general north-south folds seen over most of Rhode Island and Connecticut, while the later stress was at right angles to this and produced the east-west folds in the Narragansett Basin. This conclusion can be substantiated only partially in the Stonington region. The

¹ Foerste, U. S. Geol. Surv., Mono. 33, p. 134.

² G. F. Loughlin and L. A. Hechinger, An unconformity in the Narragansett Basin of Rhode Island and Massachusetts. *Am. Jour. Sci.*, Vol. 38, p. 53, 1914.

³ The probable Permian age of the conglomerate was first suggested by Woodward, Mono., 33, p. 184-7, but has been proved on structural grounds by Loughlin in *Am. Jour. Sci.*, Vol. 38, p. 54, who also cites obscure fossil evidence found by David White, 1914.

⁴ G. F. Loughlin, *Loc. cit.*, *Am. Jour. Sci.*, Vol. 38, p. 57.

Sterling granite follows east-west strikes in the greater part of the area and changes to north-south lines only on the eastern side of the region. The reason for this may be the resistance set up by the Preston gabbro to the northwest which offset locally the tendency to north-south folding noted in neighboring regions.

There was, however, a period of distinct north-south stress later than the Sterling invasion as is shown by the system of parallel east-west dikes of monumental granite. At the time of the last orogenic movement at the close of the Permian the strain may have been relieved in the Stonington region by great southward dipping east-west faults or shear zones, which were then invaded by the monumental rock. If the pressure was thus relieved along certain definite lines, it may account for the lack of strain seen in the younger members of the Sterling group to the south as contrasted with the varieties farther north. It would also disprove Dr. Loughlin's assertion that the post-Permian orogenic movement was not accompanied by igneous intrusions.

The diabase dikes are probably of Triassic age.

SUMMARY.

The time relations of the igneous rocks and their associated sedimentaries to other rocks and the periods of stress are believed to be as follows:

	Stonington Region	Correlation
Triassic	{ Associated veins { Dikes of diabase (Dikes of monumental granite	Diabase of Connecticut Valley. { Narragansett Basin { North-south stress Folding of Dighton conglomerate
Permian		Dighton conglomerate
Late-Pennsylvanian	{ Pegmatites and quartz { Redstone (Sterling Batholith { Alaskite { Granite gneiss	Diminishing stress East-west stress locally offset in Stonington region
Middle-Pennsylvanian		Kingston sediments
Pre-Pennsylvanian	(Stonington gneiss)	
Pre-Cambrian	(Ancient schist series)	{ Putnam gneiss, Plainfield quartz schist of Connecticut { Blackstone series of Rhode Island and Massachusetts.

PHYSIOGRAPHY

In mapping the geology of the Stonington region, the writer has been interested in testing the contrasting hypotheses used in interpreting the accordance of summit levels in southern New England. The problem is particularly important for the physiographer because it concerns the origin of an extensive older erosion surface, the so-called Cretaceous peneplain,—whether that surface was developed as the result of subaerial or marine erosion.

TOPOGRAPHY OF THE REGION

The topography of the Stonington region consists of two strongly contrasting types. One of these is the narrow belt of rough land which extends eastward along the coast from Watch Hill, R. I., and also westward on Fishers Island. This area is practically devoid of rock outcrops and its knob-like hills, irregular ridges, and undrained depressions mark the position of a well-developed terminal moraine. North of the morainal belt the hills consist chiefly of bedrock, more or less covered with till, and increase in height toward the northwest. Many of the hills are isolated, but in some localities they merge for five or six miles to form an almost continuous upland between drainage lines. Many of the individual hills are a mile or more in their longer dimension, are broad, and all have noticeably flat tops (Fig. 2).

At a distance the sky line, formed by the coalescing outlines of many hills, is remarkably even. On closer examination, however, it is seen that the upland level is not an unbroken slope toward the sea, nor is it a rolling topography suggestive of subaerial erosion alone, but that the parts really constitute a series of broad low steps or terraces.

To restore a general picture of this upland surface a system of projected profiles was used. For this purpose the region was divided into strips, averaging about two and one-half miles in width, and paralleling the major valleys. Profiles of the divides between the north-south valleys, and of the tops of the hills within the same strip, were projected on the same plane. The results are shown in Fig. 2. It will be seen that there is considerable level land and an accordance of hill tops at elevations which correspond over the whole area.

The elevations of the several terraces, or benches, shown on the profiles, are as follows:

1. 80-120 feet, which may be called the 100-foot level.
2. 200-240 feet, " " " " " 200-foot level.
3. 280-320 feet, " " " " " 300-foot level.
4. 380-420 feet, " " " " " 400-foot level.
5. 480-520 feet, " " " " " 500-foot level.

There is another possible terrace at 40-60 feet above sea level which is fairly well shown around Stonington but elsewhere is so modified by glacial deposits that it will be disregarded.

An analysis of these profiles, combined with a study of the field itself, leads the writer to believe that these levels were produced, most probably, by wave action. The flatness of the upland patches at different elevations, combined with the development of corresponding levels on the several interfluvial ridges, shows the work of a common erosive agent. That each level abuts against distinctly higher hills and that the line separating any two levels roughly parallels the present shore, and not the river valleys, seems to indicate that wave erosion was the most important agency in the formation of the benches. When it is also found that these levels correspond over wide areas, and that it is thus possible to draw approximate shore lines to show the extent of these former sea advances, the hypothesis of origin by wave erosion takes on an increased probability (Fig. 4).

The vertical distance between terraces (about 100 feet) is so small, and the scarps are now so gentle, that the unaided eye generally cannot differentiate the various levels in the field at distances of a mile or more. At the southern end of Wintechog Hill, for instance, the upland narrows and drops to the 300-foot level within a quarter of a mile. A view taken from the top of Pitcher Mountain, two and one-half miles east of this point, shows this drop in the middle of the sky line (Plate VI, a.). It will be noted that the 300-foot level, which is seen at the left, is not readily distinguished from the 400-foot level of Wintechog Hill on the right. The difference is brought out, however, and the scarp between the two levels readily located, by holding a straight edge parallel with the horizon line in the left part of the view.

RELATION OF THE TERRACES TO THE GEOLOGY

There would be little value in a study of this kind unless the hypothesis can be eliminated that such terraces may be due to dif-

ferences in rock structures or hardness. Fortunately the geology has been worked out so that this hypothesis may be tested.

The best profile, showing all the terraces, is undoubtedly that of the long divide extending south from Barnes Hill through Swantown and Wintechog Hills to the shore. The line may be continued northward to Bay Mountain in Voluntown. The geol-

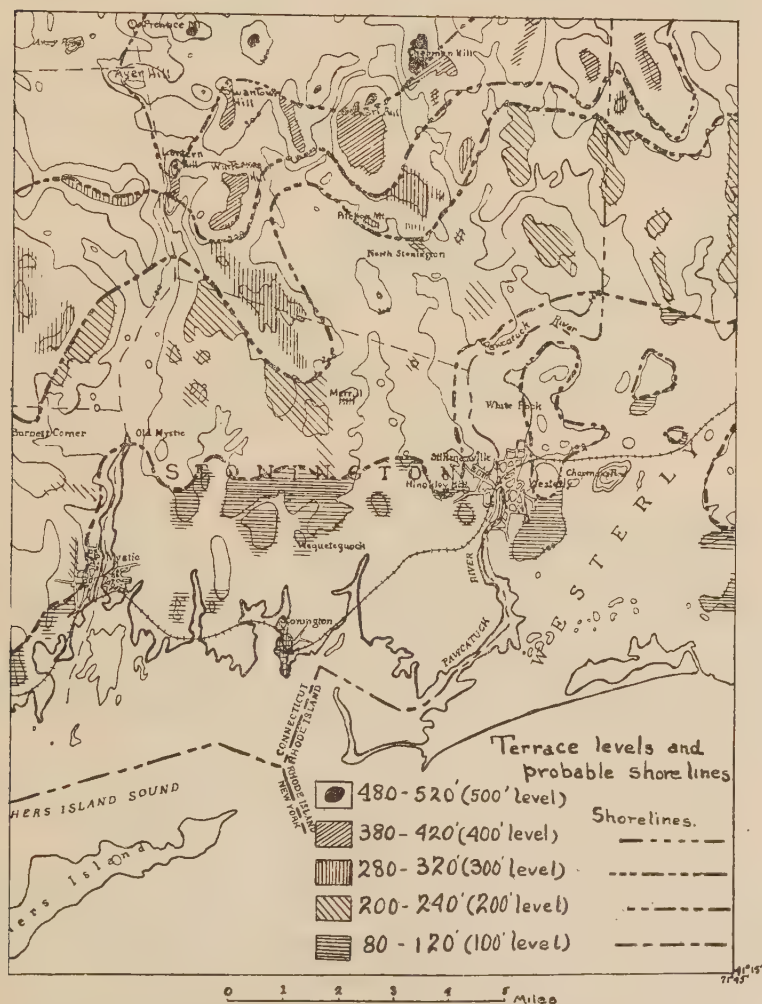


FIGURE 4. Map of Stonington quadrangle showing terrace levels and probable ancient shore lines. Contour interval, 100 feet.

ogy along this line is shown in Fig. 5. Four distinct levels are seen which show no relation whatever to the rock structure. The 300-foot level is distinctly shown in Fig 2, E, and Fig. 5, covering a considerable area, and there is probably no error in considering it a separate terrace.

The best terraces are found on the hard rock, but are not due to differences in hardness, for the same rock, such as alaskite or granite gneiss, shows terraces at different elevations.

The most resistant rock of the region is the quartz mass of Lantern Hill, and here one might expect evidence of wave erosion at more than one level, if the hypothesis of successive periods of

FIG. 8.



FIGURE 5. Geology along divide extending south from Wintechog Hill (Line B-B, Geologic Map, p. 12), and continued north to Bay Mountain (Moosup Quadrangle). Geology by Dr. G. F. Loughlin, U. S. Geol. Surv., Bull. 492, 1912, and by the writer.

wave erosion is correct. Such evidence appears to be present, for the profile of the hill shows the 400-foot level well developed over the middle portion (Long Hill), and there is a perceptible notch on the southern side at about the 300-foot level. At the northern end, also, a portion of the hill still reaches the 500-foot elevation. This higher knob at the northern end strongly suggests that marine, rather than subaerial, erosion cut the 400-foot level above which it rises.

POSSIBLE ERRORS IN INTERPRETING THE TOPOGRAPHY

Glacial modification.

Continental ice modified the pre-glacial surface somewhat by scraping it and depositing drift in places. The rock hills were little changed, however, as they are not *rôche moutonnée* forms, but still retain their flat tops. Many show small knobs on their northern ends (Swantown, Cassadock, and Wintechog Hills, as well as Lantern Hill), which may be explained as remnants pro-

jecting above wave-cut surfaces, for it would seem that such knobs should be the first to disappear under strong glacial carving. Because the region has been covered to a greater or less depth with glacial drift, it is not possible to picture the exact preglacial surface, nor is it known whether marine deposits are present or absent on these terraces. It is possible that such deposits may be present but have not yet been differentiated from the abundant glacial deposits of the region.

Possible inaccuracies of the map

Errors in the determination of the different levels might exist because of inaccuracies of the map. In this region, however, the tops of the hills were accessible at the time the surveys were made, and their elevations were presumably determined with approximate accuracy. The early roads, far from shunning the hill tops, were either the shortest routes between points, as the Providence-New London turnpike, or were laid out on the broad upland areas to avoid, as far as possible, the swampy or sandy lowlands in the valleys. The very flat, relatively good farm land on these hills led to their early clearing.

Nature of surface on which terraces were made

Up to the time of Prof. Barrell's masterly presentation of the hypothesis of marine planation in relation to the piedmont region of the Northern Appalachians¹, the idea held sway that two main subaerial erosion periods were accountable for the principal physiographic features of the eastern United States. The greater erosion surface, commonly called the "Cretaceous peneplain", was supposed to have been a continuation of the erosion surface on which the Cretaceous sediments are found in the Coastal Plain, and to have extended over most of the present Appalachian and New England regions. The flat topped hills and approximately accordant summit levels throughout the eastern United States have been supposed to be remnants of this old erosion surface. The Cretaceous plain was then supposed to have been uplifted, tilted and domed, and the areas of softer beds reduced to a second peneplain of lower level in Tertiary times. In the Stonington region

¹ Originally presented at New Haven in 1912. Abstracts in Bull. Geol. Soc. Amer., vol. 24, pp. 688-696, 1913, and recently published posthumously and edited by H. H. Robinson, in Amer. Jour. Sci., 4th ser., vol. xlix, pp. 227-258, 327-362, 407-428, 1920.

all traces of two such erosion surfaces, if they ever existed, have been obliterated.

It is impractical to conceive of an erosion surface that would include all the broad flat tops of the hills at the various levels when their relation to the geology is taken into account. Such a surface would have to be warped along the very sinuous shore lines, and along each line would have to be warped exactly the same amount over the whole area. There would have to be four distinct vertical down-folds if the broad areas at the 500-foot, 400-foot, 300-foot, 200-foot and 100-foot levels are considered parts of it. If they are, then why should Lantern and Ayer Hills and Prentice Mountain, which rise from broad areas at the 400-foot level, all reach to the elevation of the broad upland patches farther north? Nor can any one level for the peneplain be worked out, for then the accordance of levels above and below it must be accounted for. Partial baselevels are seen along the river valleys, but they are as difficult to reduce to any one erosion surface as the tops of the hills.

The only clue to the position of the Cretaceous peneplain within this region is found in a well-boring on Fishers Island.¹ Bed-rock is found 280 feet below sea level and is overlain by clay similar to the Cretaceous material on Long Island. If this depth may be taken as the position of the peneplain three miles from the Connecticut shore, the slope becomes 90 feet per mile. This slope continued across the Stonington quadrangle would rise far above the present surface. The peneplain might, of course, be warped to correspond to the tops of the higher hills, but if so, it would change from a slope of 90 feet per mile to one of 14 feet per mile within a distance of eight miles from the coast. It could not, however, be made to include the best flat areas without the complex warping mentioned above. In any case, the peneplain surface is practically unrecognizable in the region, the topography having been entirely recarved by subsequent erosion.

Although there is no distinct evidence of the Cretaceous peneplain, there is a suggestion that the region was at one time reduced to a surface of little or no relief, and covered with coastal plain material. This is apparent from the superposition of some of the

¹ M. L. Fuller, *Geology of Fishers Island, N. Y.*, Bull. Geol. Soc. Amer., vol. xvi, pp. 367-390, 1905.

streams on very hard rock; the Shunock-Pawcatuck River, for example, probably would not have crossed Redstone Ridge at Westerly unless let down upon it.

The superposition of the lower Connecticut, and the southeast courses of other rivers in southern New England, dates undoubtedly from a period when an erosion surface was mantled with enough marine material so that on uplift the rivers flowed to the southeast regardless of the underlying structure. This southeast course of the rivers is shown best in the Connecticut and Housatonic, and also in some of the upper tributaries of the Thames. But the lower course of the Thames, and practically all the smaller rivers in the shoreward part of Connecticut, show a decidedly north-south arrangement, as in the Stonington region. This seems to call for another advance of the sea at a later date, with a coating of marine sediments to obliterate the southeast trending valleys near the sea. After this advance the land rose uniformly, causing many of the streams to take a southerly, as contrasted with their former southeasterly, course to the sea. The change from a southeasterly to a southerly course is most clearly shown in the lower Housatonic, and it is to be noted that the higher hills reach the 500-foot level near the locality where the course of the river changes in direction.

It is thus believed that there was an incursion of the sea which developed the terraces at the 500-foot level, and that the topography of the Stonington quadrangle dates only from that incursion, whatever its date.

Whether the 500-foot level was a peneplain of subaerial erosion which was covered by marine sediments as the sea advanced, or whether it was carved out primarily by the sea, cannot be told. The writer believes that at least its final form was due to wave erosion, because of its similarity to the terraces at lower elevations which so strongly suggest a marine origin. The lower terraces were probably carved out of what remained of this 500-foot plain after extensive subaerial erosion had taken place. The subparallel bending inward of the shorelines along river valleys, shows that at no later date, however, did the sea obliterate all marks of the previous river erosion.

While wave planation was going on along the shore, subaerial forces were doing much to remove the higher land in the interior.

Thus the extensive lower surfaces along the Quinebaug were probably developed while the waves were attacking the very resistant rocks farther south. The difference in the amount of flat upland north and south of the group of high hills in North Stonington and Voluntown is significant of the difference in the two erosional processes.

Indistinct benches, 50-60 feet above the terrace levels, can be seen in many of the river valleys to the north and in the upper levels of the smaller hills. These probably show the temporary baselevels established in the river valleys corresponding to the different sea levels shown by the terraces in the Stonington region.

GLACIAL GEOLOGY

INTRODUCTION

That the Stonington region was glaciated during Wisconsin time is abundantly proved by the topography, the drainage systems, and the character of the unconsolidated deposits. All the unconsolidated formations, except the recent swamp and beach deposits, were laid down by the continental ice sheet and its attendant subglacial or extraglacial waters. The distribution of these deposits in the eastern part of the region, which is typical for the region as a whole, is shown in Fig. 6.

The effects of glaciation are seen in the scraped and rounded rock surfaces and in the thin coating of very coarse drift that covers the hills. Glacial grooves and striations are common and are especially well seen on most freshly uncovered rock surfaces. The best defined scratches trend between N. 2° W., and N. 24° W., and in many localities two sets of striae are seen on the same rock surface, differing in direction as much as 20 degrees. Those striae which trend between 15 and 20 degrees west of north are approximately at right angles to the terminal moraine and indicate, with other evidence, the southward direction of the movement of the ice sheet during its last advance. Those having a trend more nearly north and south may show the direction of ice movement during an earlier stage of glaciation.

The oncoming ice sheet removed all the loose preglacial surface material and cut to some extent into the solid rock below. The amount of erosion, however, was not uniform. The retention of the flat upland surfaces shows that the ice was not powerful

enough to reshape the hills markedly. On the other hand the ice seems to have done considerable cutting on northwest slopes. East-west spurs were probably prominent in this region in preglacial time, for the rocks are of unequal hardness, and a submature stage

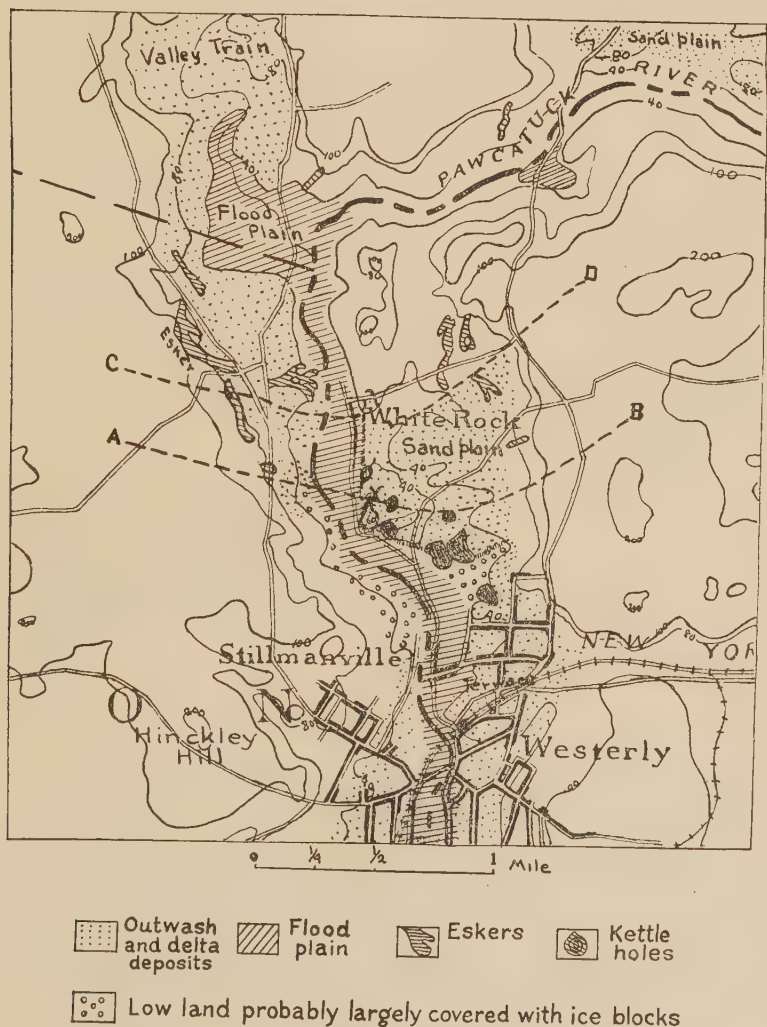


FIGURE 6. Fluvio-glacial deposits near White Rock and their relations to the present floodplain, and the probable positions of the ice front.

High level delta south of point X on line A-B. Contours drawn at 40, 80, 100 and 200 feet above sea level.

of erosion is indicated by the uplands. The absence of such spurs, and the great breadth of the valleys as compared to their length, show that the north-south drainage lines were probably considerably widened and straightened by glacial ice.

Huge boulders scattered throughout the region show that the ice was a powerful plucking agent. The largest are joint blocks which were broken off from the vertical cliffs seen in so many places. These cliffs are generally nearly parallel with the direction of ice movement, the trend of those best developed being N. 18° E., N. 2° E. or N. 12° W. There was, however, little rounding of the sharp edges of either the blocks or the cliffs. The largest observed block measured 20 by 40 by 50 feet.

On the whole, glacial erosion probably did not greatly change the topography of the region; the shapes of the hills remained essentially the same, only subdued slightly in outline. This may be explained by the fact that the ice sheet, which at its maximum extended only 20 miles farther south, must have been relatively thin and ineffective in this region.

Under the ice, especially near its terminus, were streams of water, which here and there carved channels in the underlying rock. A small channel of this nature is well developed on an inclined rock surface in a ledge of contorted hornblende schist on Quarry Hill in Westerly. It is 15 feet in length, irregularly curving, and ranges in width from 8 inches to 3 feet, and in depth from a few inches to a foot, and is shown in Plate V, b.

THE TERMINAL MORaine

The pronounced terminal moraine extending northeasterly from Watch Hill is part of the inner, or Harbor Hill, moraine of Long Island (shown by two dotted lines in Fig. 7), which is commonly accepted as marking the maximum advance of the continental ice sheet during the late-Wisconsin stage of glaciation. The material of which it consists is chiefly tan-colored clay, containing many boulders both of large and small size, and irregular patches of roughly stratified sand.

The moraine is easily recognized and is a striking scenic feature along the coast. The topography needs no special description, as it is typical in every respect. The "kame and kettle" feature, however, is admirably developed and may be seen very

advantageously near Watch Hill. In fact, this hummocky ridge has been justly called one of the "finest examples of glacial dumping grounds in the East."¹

GROUND MORAINE

North of the terminal moraine the drift shows great irregularity in distribution and thickness. The broad flat tops of the hills have a substantial coating of till, but the slopes, especially if steep, show more or less extensive outcrops of bedrock. Only rarely is



FIGURE 7. Map showing connecting reefs between Fishers Island and Watch Hill. Submarine contours drawn at 6, 12 and 18 feet depths. Drawn from Coast and Geodetic Survey Chart No. 358, 1911.

a hill found that is entirely till covered. Williams Hill, two miles east of Mystic, is of this nature, and its long oval form indicates that it is undoubtedly a true drumlin. On the hills the drift consists of buff-colored sandy clay containing boulders three to eight feet in diameter. Most of the boulders are local in origin, but several, including some very large ones, were transported a considerable distance. The largest erratic noted in the region is more

¹ J. F. Kemp, The granites of southern Rhode Island and Connecticut. Bull. Geol. Soc. Amer., vol. 10, p. 362, 1899.

than 10 feet in diameter and, as it consists of Preston gabbro, must have been transported at least seven miles.

Weathering has affected the upper 12 to 18 inches of the drift, changing its color from light tan to brown. The soil proper is never very black and is only three to four inches thick. Even in the weathered zone, most of the stones are still fresh, except those of dark schist which are generally rotten not only near the surface but at depths of several feet.

FLUVIO-GLACIAL DEPOSITS

When the ice sheet stood along the line marked by its terminal moraine, much material was deposited by glacial streams on the lowland to the south, building up an outwash plain. North and east of Brightman Pond the plain gives way to outwash-covered ground moraine, with large boulders and bedrock outcropping here and there. The outcrops of bedrock show that the deposit is rather thin in this locality. The few cuts made in the material show roughly stratified sands and gravels, the latter including some beds of large cobbles. After the ice melted back from the terminal moraine the glacial waters were concentrated in the pre-existing valleys and on the lowland to the north.

Fluvio-glacial material is found in most of the lowlands, rising in places 20 to 80 feet above river levels. These deposits were clearly made as the ice melted off the region for the last time. A well driven in the Pawcatuck valley at White Rock, and also one at Bradford, however, show that fluvio-glacial material extends 60 to 90 feet below sea level. At White Rock this deeper material is separated from the fluvio-glacial material above by a layer of clay six feet thick, but at Bradford the layer of clay just below river level is lacking. It is not possible to say whether or not all the fluvio-glacial material to a depth of 90 feet or more below sea level was deposited during the final retreat of the ice. For a time blocks of ice remained over much of the land abandoned by the glacier, and in places were sufficient to dam the extraglacial streams, producing local lakes. The presence of these stranded masses of ice seems to account for: (1) the kettle holes and other phenomena associated with the sand plains, (2) certain low portions of valleys which are free from fluvio-glacial deposits, and

(3) the local lakes in which much of the fluvio-glacial material appears to have been deposited.

TERRACES

Small, discontinuous sand and gravel terraces, rising 15 to 25 feet above the river are found along the east side of the Pawcatuck between one and three miles south of Westerly. Their flat tops and steep fronts suggest that they were deposited as deltas in local lakes rather than in the sea. These deltas lack the continuity and accordant summits of marine terraces, and one also fails to find wave action or shore features on the outside of the moraine to prove a lower stand of the land while these deltas were being built, or later. The lack of fluvio-glacial deposits along the southwest side of the present embayment of the river suggests the presence of considerable ice over parts of the lowland, probably enough to form the small lakes.

Westerly and Stillmanville are built on terraces which stand about 40 feet above sea level. Numerous excavations show relatively fine stratified and cross-bedded material overlain by six to ten feet of the coarsely stratified drift. At Stillmanville the capping material is particularly coarse, the boulders ranging from six inches to two feet in diameter. The Westerly terrace is quite flat, but improvements in connection with the building of the city make impossible a detailed analysis of its form.

THE WHITE ROCK SAND PLAIN

South of White Rock and east of the Pawcatuck is an interesting accumulation of fluvio-glacial deposits, the largest and most complex in the Stonington region. The deposits are practically continuous with those at Westerly farther south, and are undoubtedly connected with them in origin.

The White Rock sand plain rises abruptly from the floodplain of Pawcatuck River (Plate VI, b, and Fig. 8). It is generally flat-topped but is pitted with a number of roughly circular kettle holes 100 to 300 feet in diameter and 20 to 35 feet deep. Along its southwest border is a patch of flat land, about one-eighth mile in length and 50 to 100 feet in width, which rises 20 feet above the plain, or 65 feet above river level.

The sand plain has a smooth outline where Pawcatuck River has cut a steep erosion face (Fig. 8). Elsewhere the border is very irregular, particularly on the southeast where there are several projections resembling eskers which lose their flat tops within a few feet of the sand plain. The reëntrants in the sand plain between them generally head in bowl-shaped depressions similar to a kettle hole with one side lacking.

The terrace on which Westerly is built extends within a few hundred feet of the White Rock sand plain, and in the area between them are broad, irregular depressions, occupied by peat

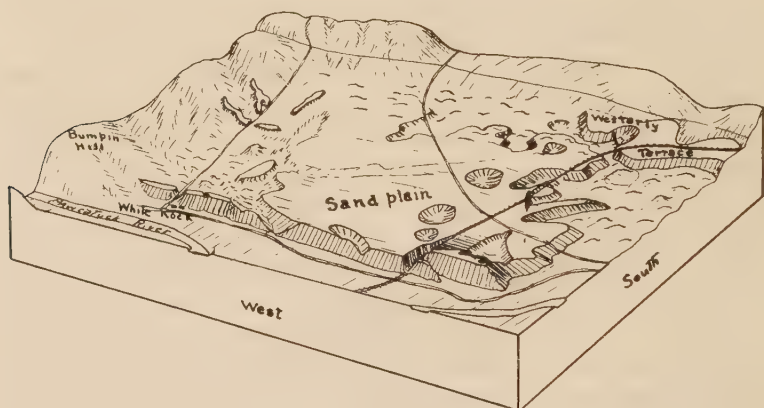


FIGURE 8. Block diagram illustrating the relations of the White Rock sandplain to the Pawcatuck River and neighboring hills and lowlands. View from southwest.

bogs. Although the sand plain and terrace are near together and stand at the same level, there is no evidence that they were once joined and later separated by post-glacial erosion. Along its northeast border the sand plain, interrupted with kettle holes and irregular depressions, merges into the ground moraine on the adjacent hill slope. On the north, a lowland separates the sand plain from the rock hills and marks the position of the ice edge, during the time when most of the sand plain was being constructed. (Line C-D, Fig. 6).

The material forming the sand plain is similar to that of outwash deposits but generally better stratified. Most exposures show two distinct parts, a lower of finely stratified deposits, horizontal or steeply dipping, and an upper of horizontal, coarsely stratified

material. In places, also, the lower beds include cobbles up to nine inches in diameter, well set in stratified sand, which seem to imply the presence of ice blocks. Contorted strata, perhaps due to the drag of such blocks just after the lower fine-grained material had been deposited, are also conspicuous features (Plate VII, a.).

This bipartite structure of the fluvio-glacial deposits is lacking in the little patch of high level sand in the southwest corner of the White Rock plain. At this place the material is approximately the same in texture and structure from the top to the bottom of the deposit, and was probably made at an earlier date or under different conditions.

The White Rock sand plain seems to have been made by the outwash of material into a valley so choked with blocks of ice as to cause ponding. Standing water was undoubtedly present for a great part of the time, as shown by the fine stratification, ice-raftered boulders, ripple marks and cross-bedding seen in the lower beds. The presence of finely stratified material at a higher level than the rest of the deposit east of the river, and an indistinct terrace on the west side of the river near the end of an esker, indicate approximately the initial water level. With the retreat of the ice to the north and the lowering of the level of the standing water to not less than 30 feet above the present river, the lower beds of the rest of the sand plain were deposited. These seems to have been laid down in standing water very near the edge of the ice. The upper horizontal beds were probably deposited as subaerial outwash on the lower delta beds, either because the lake drained away or because the lower beds had been built up to the water level. The process seems to have been continuous for the great blocks of ice included in the delta deposits persisted until after the whole series was deposited.

The lowland must have been largely covered with ice blocks to account for the blunt headed reëntnants and finger-like projections of the sand plain. As the small projecting ridges are not delta fingers and have not been isolated by post-glacial erosion, the conclusion seems reasonable that they were deposited as the rest of the sand plain was, but between great blocks of ice.

The original size of the sand plain, the area occupied by ice blocks, and the extent of the temporary lake cannot now be exactly determined. The glacier itself held in the lake on the north, and

probably stood along the line A-B (Fig. 6), while the high level delta was being deposited, and then retreated to the line C-D while the rest of the sand plain was built. On the south the lake probably extended about one mile south of Westerly, for the level of the Westerly terrace corresponds closely with the general level at White Rock plain and from there southward great fluvio-glacial accumulations on both sides of the valley are lacking.

The structural features seen in the White Rock sand plain are duplicated to a certain extent in other similar deposits of the region. At Potter Hill, finely laminated sandy clay underlies coarse outwash, and has been used for the manufacture of brick.

The sand plains of the region stand at different heights, and in some the delta structure extends to the top, as at Ashaway, so that local conditions undoubtedly governed deposition and there was no widespread lake or higher sea level at any time during their formation.

ESKERS AND VALLEY TRAINS

Much material was carried forward to the White Rock sand plain by subglacial streams, and eskers lead into the Pawcatuck valley from the west and north. Those streams that helped to build the delta when the ice stood along the line A-B (Fig. 6) deposited material in their channels which was later partly covered by the delta when the ice retreated to the line C-D.

A strong subglacial stream came in from the northwest, for several eskers are located along the Pawcatuck-Shunock valley. These eskers are not continuous, nor very large, but are well formed and in places extend 40 to 60 feet up the sides of the hills. The distribution of these eskers is shown in Fig. 6. The largest esker sends one branch to the east which terminates in a number of distributaries running east and southeast on top of a small rock hill just across the valley from White Rock. These distributary ridges are most interesting, for although they cap a rock hill, yet they enclose a perfectly formed, deep, steep-sided kettle hole. Another branch continues south along the west side of the valley and undoubtedly was the chief line of subglacial drainage into the lake when the ice stood along line A-B (Fig. 6). Small eskers, extending down the sides of the rock hills, occur also in other parts of this particular region.

A typical valley train occurs in the valley of Shunock River and in the Pawcatuck valley north of White Rock. It is gently undulating, rises gradually to the north, and for the most part consists of very coarse and poorly stratified material. Irregularities of the surface are due chiefly to the unequal thickness of the underlying till and to knobs of rock, many of the latter rising like islands from the gently sloping plain. The valley train also contains kettle holes and uncovered low places in much the same relation as at White Rock, showing that ice blocks were not lacking.

GLACIAL LAKE BEHIND THE TERMINAL MORaine

Water also undoubtedly accumulated back of the terminal moraine during the retreat of the ice, and a shallow lake once occupied the marsh-covered lowland east of Westerly. Just what were its relations to the lakes in the river valleys, and how far it extended cannot now be told, for the lake was evidently too short-lived to develop well-defined shore lines. Its existence, however, is shown by the perfectly flat plains between the present swamps and lakelets, by the subdued character of the ground moraine near this low level, and by finely laminated sands overlying the till. Further evidence of this lake is found in the ancient stream channel between Quarry Hill and the terminal moraine south of Westerly. The floor of this well-defined valley is covered in places with heavy boulders which the small stream now occupying the valley is incapable of handling. Toward the end of its existence the lake was probably very shallow, for a rise of only a few feet in the level of the swamps would cause a considerable volume of water to take the more direct route of this ancient outlet to the sea. The decrease in the supply of water as the ice left the region, and the melting of the ice blocks in the fluvio-glacial deposits in the valleys, was evidently sufficient to lower the lake level so that it was eventually drained by the present Pawcatuck River.

EVIDENCE OF MORE THAN ONE STAGE OF GLACIATION

The great bulk of the known unconsolidated deposits of the region was laid down by the continental ice sheet, and its attendant waters, when the ice stood along the line of the terminal moraine and later when it finally retreated from the region. This stage of glaciation is called the late-Wisconsin. There are, however, sev-

eral localities where evidence is found of an earlier advance of the ice which extended farther southward. This stage is commonly known as the early-Wisconsin.

One of these localities is at Weekapaug on the Rhode Island shore, east of Watch Hill, where glaciated rock surfaces and till occur south of the terminal moraine of the region. The till is indistinguishable from that found north of the moraine. Another locality is on the outer side of the terminal moraine just east of Watch Hill, and shows very perfectly stratified sandy clays cut off unequally and overlain by six feet of very coarse till. The presence of water to the south suggests that the sandy clays may be an interglacial marine deposit, in which case a considerable change in altitude of the land would be indicated between the deposition of the two deposits. The stratified beds, although unidentifiable

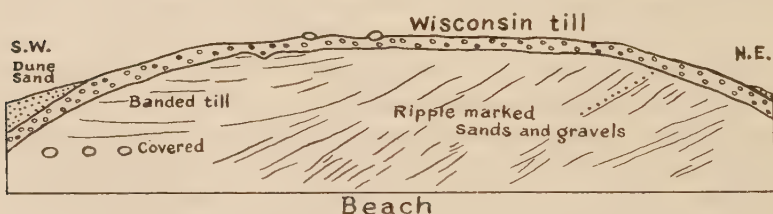


FIGURE 9. Diagram of sea-cliff at Watch Hill. Stratified sands and gravels grade upward into banded till and sand layers, and are overlain by a layer of Wisconsin drift and dune sand.

in this place, are very much like the Jacob sand described by Fuller¹ from Isabella Beach, Fishers Island.

Near Watch Hill Point similar evidence is found. The point itself is a boulder platform resulting from the removal of the lighter drift material by the waves. The first hill to the northeast is part of the terminal moraine proper, and is the highest point on the shore for many miles. On the landward side it is an ordinary round hillock, strewn with boulders and recent dune sand, similar to many other knobs in the moraine. It rises 50 to 60 feet above the sea, and nearly half of it has been cut away by the waves. The eroded face (Fig. 9) shows the hill to consist chiefly of stratified sands and gravels, above which, and making an angular uncon-

¹ M. L. Fuller, Geology of Fishers Island, Bull. Geol. Soc. Amer., vol. 16, pp. 367-390, 1905.

formity with the stratified beds, is a thin layer of till similar to that found elsewhere in the region (Plate VII, b.). The till is two to three feet thick on the average but thickens on the slopes and is five to eight feet thick in a small depression near the top of the hill.

There is no doubt that the material of the lower stratified beds was washed out from the edge of a nearby glacier and deposited in water. Only a glacier could accumulate such a heterogeneous mixture of stones, some of which are subangular in shape and even retain a few striations. Local contortions and cuttings of the layers, and also pockets of gravel and incorporated boulders, show that ice blocks were probably present while the beds were being deposited.

The lower beds dip steeply toward the west (Fig. 9) and then grade upward into layers which are nearly horizontal. The latter include banded till, cross-bedded sands, and some thinner beds of coarse pink sand or fine gravel. Some of the banded till layers are a few inches, others two to three feet, in thickness, the latter carrying large boulders. But the beds traced in either direction thicken or thin decidedly within short distances, and even play out. The apparently massive till, when examined carefully, is seen to be finely laminated.

The position of these stratified beds in the outermost part of the terminal moraine suggests that they were deposited in the sea, in which case a change of 60 feet or more in the altitude of the land must have taken place before the deposition of the overlying till, for the latter shows no evidence of having been deposited in water. As this is believed to call for considerable time, the exposure may indicate two episodes in a single stage or perhaps even two stages of glaciation. Upholding the latter view is the suggestion of an erosional interval between the stratified beds and the till. The evidence is a little depression, apparently a small stream channel, in the top of the stratified deposits. It is well seen, although only four feet deep, because the filling of till contains conspicuous white boulders (Plate VIII, a.). There is also a suggestion of an earlier weathered zone in the yellow gravels and sands which lie just below the till.

Before two glacial advances of considerable importance can be postulated for the region, however, marine fossils or other positive evidence of the marine origin of the stratified beds would have

to be found. The short subaerial erosion interval between the two deposits may mean only a withdrawal of the ice front for a short distance, exposing previously deposited outwash beds. The re-advance of the ice in this case would be only a short episode in the retreat of the glacier.

An exposure on the eastern border of the region is interesting in this connection. At Newhall's new quarry, at Bradford, a cut shows till, three feet deep, overlying peculiarly contorted stratified beds, which in turn are underlain by till (Plate VIII, b.). The upper till is similar to the Wisconsin till seen elsewhere, except that it is somewhat less sandy, and contains boulders two to five feet in diameter. The lower contact of the upper till is remarkably even and has no relation in character and position to the underlying stratified beds. The stratified beds bend up very sharply over boulders in the underlying till, and break a little and thin out in so doing. The fact that the beds are as much folded below as above suggests that they were probably frozen at the time they were deformed and acted more or less as a unit.

Toward the west the contorted beds grade over to heavy gravel and finally to interbedded gravel and banded till layers, the banded till being very similar to that exposed at Watch Hill. In fact the resemblance between the deposits as a whole at these two localities is so great that the writer is inclined to correlate them with each other, and to assume that this intermediate stratified series was also deposited in the sea if the other shall prove to be marine. In this case a former depression of the land 120 feet below its present elevation would be called for.

The presence of the heavy till bed and striated rock below the banded till layers at Bradford, however, shows that the ice was thick enough to erode the submerged rock surface, the banded till evidently being formed only when the ice grew thin.

Banded till is found extensively developed on Long Island and Fishers Island, generally associated with a thick deposit of water-laid sands and gravels. These beds are called by Fuller "the Montauk till" and "Herod gravel", and are supposed to have been deposited during the Manhasset glacial stage, when the land stood 0-100 feet lower than at present. They are everywhere separated from the overlying drift by an erosional unconformity, and dur-

ing the interval thus indicated—the Vineyard—the land is supposed to have stood some 350 feet higher than at present¹.

The exposures of these beds seen on Long Island by the writer, although indicating an oscillating ice edge, are no more convincing of distinct glacial stages than those in the Stonington region. The best exposure, showing nearly the whole range of glacial deposits found on Long Island, was seen at the Phoenix gravel pit on Hempstead Bay. There the overlying drift was five feet thick but increased to about 25 feet in the old river valleys carved in the underlying stratified beds.

The writer, however, although convinced of two glacial advances over the southern part of the Stonington region, does not believe that any part of the exposed drift is pre-Wisconsin, as interpreted by Fuller for Fishers Island and Long Island. With the exception of the few exposures mentioned, which may be considered early-Wisconsin, no exposures gave any indication that the deposits were not all of the same age, namely, late-Wisconsin. It is believed that the terminal moraine does not represent a thin veneer of drift over an erosional topography, for it has all the characteristic features of a true moraine. Nor is it possible that the moraine is a pressure ridge, for bedrock outcrops through it at the bend of Pawcatuck River and north of Weekapaug, and the ice as a whole would have been resting on bedrock when its edge was along the terminal moraine.

POST-GLACIAL EVENTS

CHANGES OF LEVEL

The post-glacial drowning of the southern New England coast is well shown in the Stonington region by the embayed coast line and the submerged channels in the Pawcatuck and Mystic Rivers. The channel of Pawcatuck River, where it is known to be in solid rock at Pawcatuck Rocks two and one-quarter miles south of Westerly, has a depth of 19 feet. As this locality is three and one-half miles from the mouth of the river, an assumption of a depression of about 20 feet is probably justified. It may be noted that Fuller estimated that a former elevation of 20 to 25 feet would account for all the phenomena of post-glacial submergence seen

¹ M. L. Fuller, U. S. Geol. Survey, Prof. Paper 82, pp. 199-208, 1914.

on Long Island.¹ Moreover, there appears to be no evidence of a still lower stand of the land in post-glacial time, for late-Wisconsin till, as originally deposited, extends to present sea level in well exposed positions.

The question whether the land along the New England coast did not stand, during post-glacial time, at an elevation greater than 20 to 25 feet above the present level has been raised by both botanists and geologists.²

Fernald has stated³ that the coastal plain plants "either migrated northward on the continental shelf prior to the Wisconsin glaciation and persisted outside the subsequently glaciated area, finally taking possession of their present isolated habitats on the receding of the ice or, as seems to me perhaps equally probable, the continental shelf, including the present southwestern half of the Gulf of St. Lawrence, must have been considerably elevated after the Wisconsin, long enough for the migration, including some mammals, and even fresh water and land snails."

The botanical evidence that there was a land connection during post-glacial time between Long Island, Fishers Island, and the mainland of Rhode Island, and consequently that the land stood more than 20 to 25 feet higher than at present, is based on the following facts: (1) Southeastern Connecticut appears to have been the center of distribution of many plants which migrated from the south via Long Island; (2) certain coastal plain plants, which could not have migrated well along an unfavorable coast like that of Connecticut, are found in New Jersey, Long Island, Block Island, Marthas Vineyard, and Nantucket, and less commonly near the shore in Massachusetts and Rhode Island. On this basis an elevation of at least 120 feet would be called for, which would lay bare a considerable part of the continental shelf.

However, it does not seem necessary to account for this distribution of plants by assuming that the land stood 120 feet above its

¹ M. L. Fuller, Geology of Long Island, N. Y. U. S. Geol. Survey, Prof. Paper 82, p. 216, 1914.

² Arthur Hollick, Plant distribution as a factor in the interpretation of geological phenomena. N. Y. Acad. Sci., vol. 12, pp. 189-202, 1893.

M. L. Fernald, Botanical Expedition to Newfoundland and Labrador. *Rhodora*, vol. 13, pp. 109-162, 1911. See also, *Amer. Jour. Sci.*, vol. 40, p. 17, 1915.

G. E. Nichols, The Vegetation of Connecticut. *Torreyia*, vol. 13, no. 5, 1913.

J. Barrell, Factors in movements of the strand line and their results in the Pleistocene and post-Pleistocene. *Amer. Jour. Sci.*, 4th ser., vol. 40, p. 13, 1915.

R. A. Daly, Oscillations of level in the belts peripheral to the Pleistocene Ice Caps. *Bull. Geol. Soc. Amer.*, vol. 31, pp. 303-318, 1920.

³ Personal communication to J. Barrell, and quoted by him in his paper cited above.

present level. Seeds are often carried on the feet and in the intestines of birds, and the maximum distance of 35 miles between Block Island and Marthas Vineyard is not excessive for such a method of transportation. Wind distributes seeds, particularly of the grass family, for distances exceeding that. Reference to the Coast and Geodetic Survey charts, Nos. 1211 and 358, will show that there are numerous reefs and submerged platforms between the eastern end of Long Island and Nantucket, which, from their shape and position, are eroded portions of the same terminal moraine found in the adjacent land areas. Many of these reefs were undoubtedly islands which stood above sea level for hundreds of years but have been destroyed by wave erosion. These islands would have lessened materially the expanse of salt water over which seeds had to be transported.

Channels on the continental shelf have also been urged as proof that at some time since the ice sheet receded the land stood much higher than at present. Deep channels cut the terminal moraines, both the outer and the inner, attaining a maximum depth of 53 fathoms, so that on this basis a post-glacial elevation of 318 feet would be demanded. But these channels are seen to be best developed where the oncoming tides are most narrowly constricted, as between Long Island and Plumb Island and between Gull Island and Fishers Island. A careful study of the charts, however, leads to the conclusion that these channels, or deeps, give evidence only of scouring by tidal currents. Thus the land may have stood as much as 300 feet, or more, higher than at present in post-glacial time, but the evidence from the coast of southern New England is not wholly conclusive.

EFFECTS OF WAVE ACTION

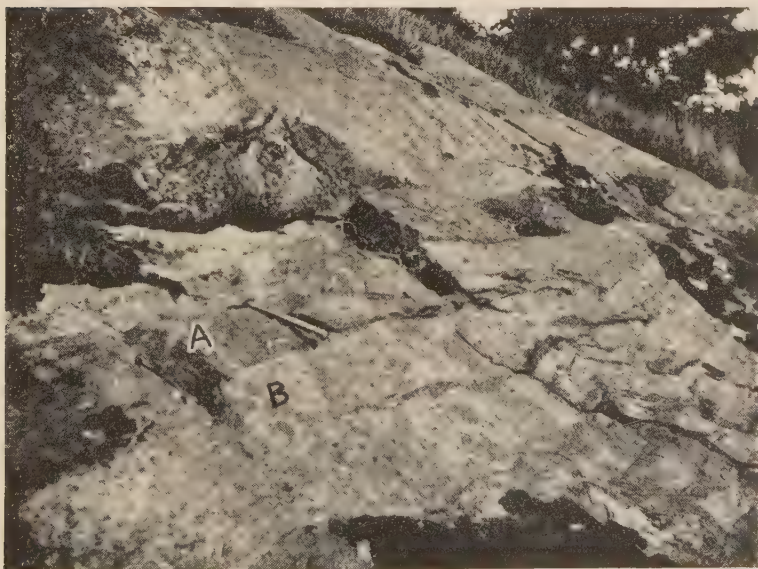
Post-glacial stream erosion has produced little change in the general topographic features except for the deepening and widening of valleys which were filled with stratified drift. Wave erosion, on the other hand, has produced some striking changes in the coast line, especially in Rhode Island, for there nothing checks the force of the waves from the open sea. The terminal moraine is being cut back at Watch Hill and the material shifted both eastward and westward by waves and tidal currents, thus giving

rise to a "winged beheadland". What formerly were island or promontories of drift have been reduced to reefs and boulder platforms just below sea level. One of the most striking results of wave work is the beach which connects Watch Hill and Napatree Point, and the hooked spit which extends northward from that point to Sandy Point (Fig. 7). This spit has grown notably and changed its shape within recent years, and particularly since 1895 when the breakwater south of Stonington was completed.

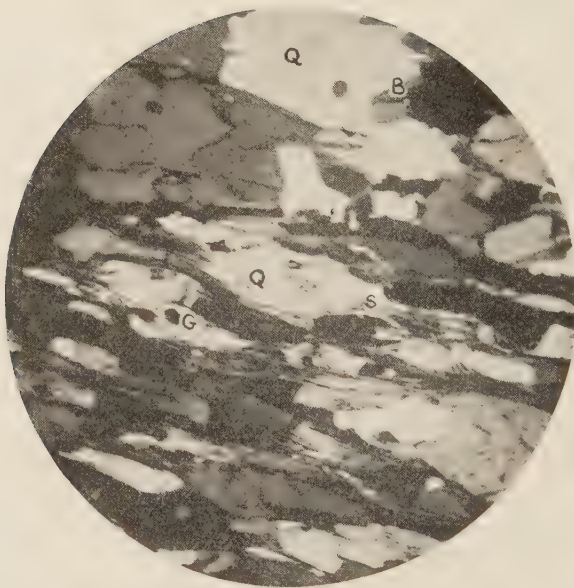
PLATE I.



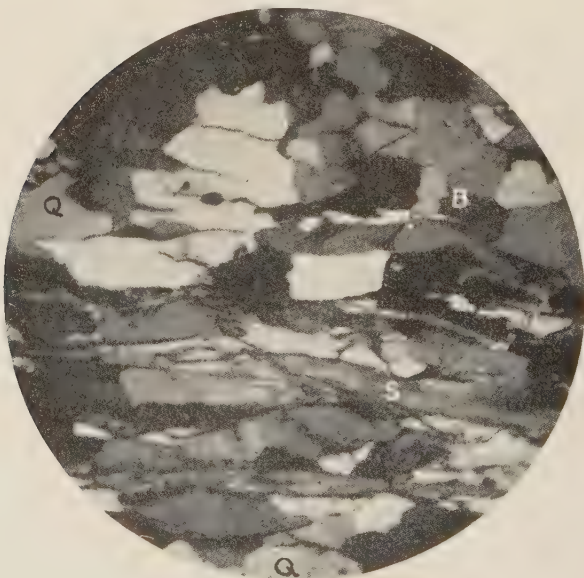
- a. Contorted quartzite, quartz-biotite schist and hornblende schist layers, injected by igneous quartz parallel to the bedding and cut by stringers of pegmatite, south slope of Diamond Hill, a mile northeast of Ashaway, R. I.



- b. Muscovitic Sterling Redstone granite invading crystallized Kingston sediments in irregular sheets, south end of Tower Hill near Wakefield, R. I. A, Kingston sediments.
B, Muscovitic Sterling Redstone granite

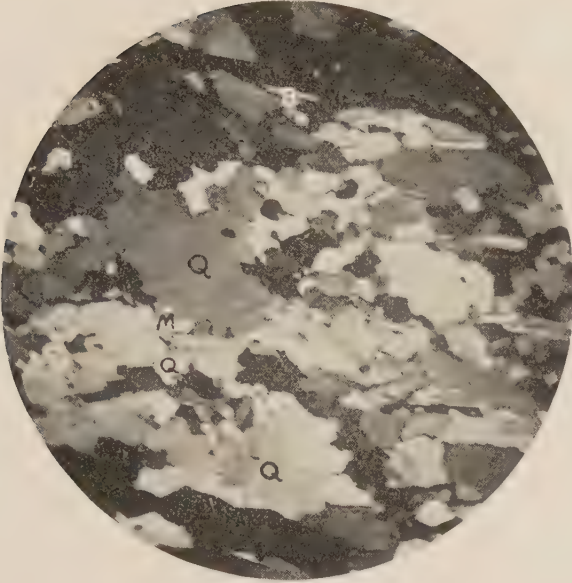


- a. Meta-conglomerate from one mile west of Ashaway, R. I. Part of a sillimanite-schist pebble is shown in the lower half of the slide, and the quartz-biotite matrix in which it is embedded in the upper half. Quartz (Q), biotite (B), sillimanite fibers (S), garnet (G). Magnified 24 diameters, nicols crossed.

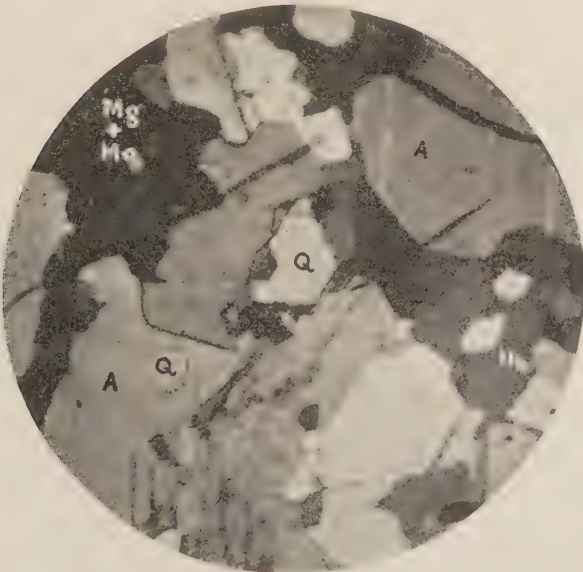


- b. Meta-conglomerate from Wordens Pond, R. I., showing similarity to the meta-conglomerate of the Ashaway region (Plate II, a). Sillimanite-schist pebble below, quartz-biotite schist matrix above. Quartz (Q), biotite (B), sillimanite fibers (S). Magnified 24 diameters, nicols crossed.

PLATE III.

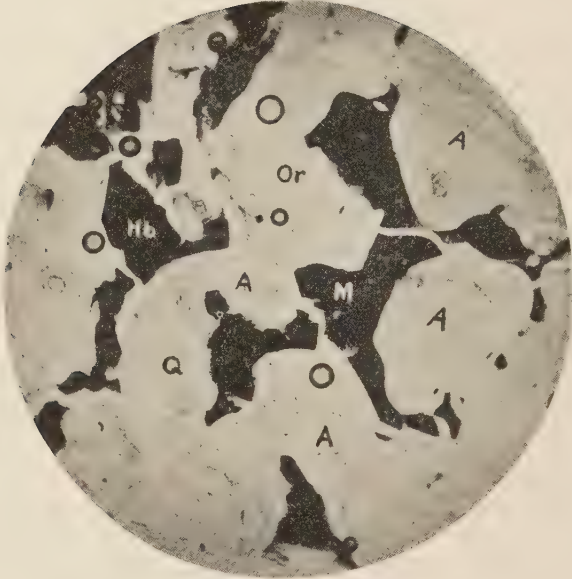


a. Meta-conglomerate from southwest corner of Narragansett Basin. Quartz (Q) in large and small grains, biotite (B), muscovite (M). Magnified about 24 diameters, nicols crossed.

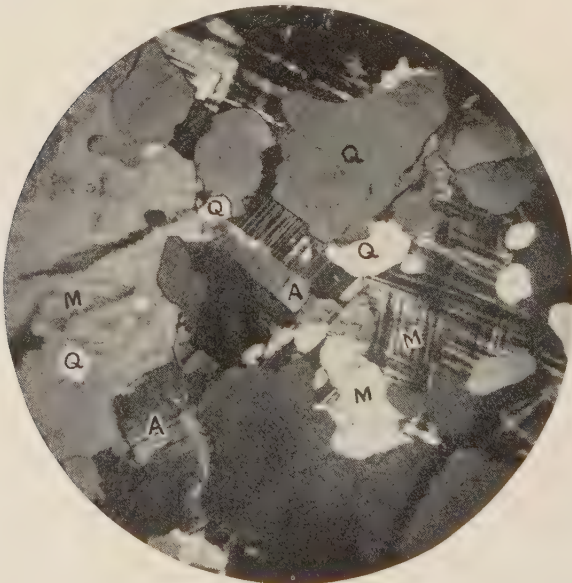


b. Stonington quartz-diorite. Andesine (A), hornblende (Hb), quartz (Q), large magnetite grain (Mg), surrounding monazite crystals (Mo), seen on left. Magnified 24 diameters, nicols crossed.

PLATE IV.



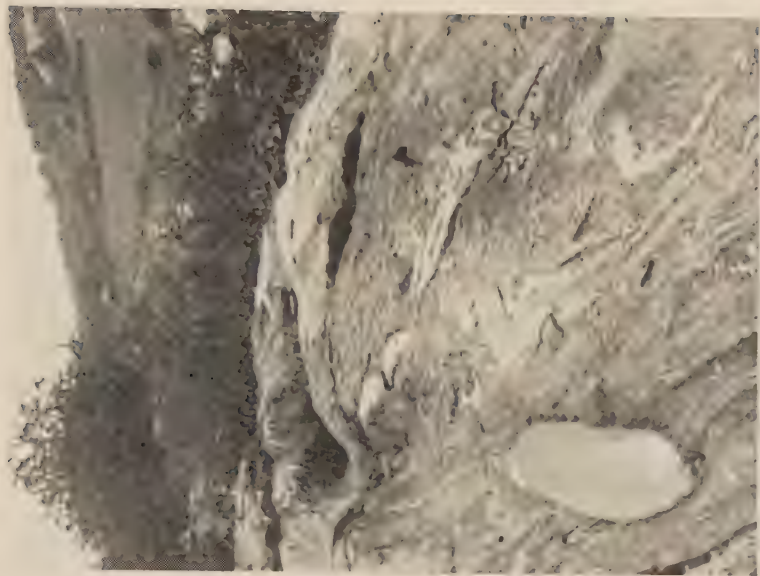
- a. Basic segregation or inclusion in Stonington quartz-diorite showing magnetite (M) in an interstitial position between andesine (A), quartz (Q) and orthoclase (Or). Hornblende (Hb) on the left is in much the same relation. Cracks in the slide unfortunately separate the minerals. Magnified about 24 diameters. Ordinary light.



- b. Alaskite from hill, northwest of Ashaway showing micro-faulting in albite (A) in center. Other minerals are microcline (M) and quartz (Q). The black streak in the large microcline crystal on the left is a crack filled with limonite.



a. Garnetiferous, hornblende pyrite-plagioclase mass in Stonington gneiss (quartz-diorite), probably showing assimilation of lime-magnesian rocks, Stonington Road near Wequetequock.



b. Schist with granite stringers showing varying degrees of folding. Curved groove is subglacial stream channel. North end of Quarry Hill, Westbury, R. I.

PLATE VI.



- a. Drop between the 300-foot and 200-foot levels at the southern end of Wintechog Hill. View taken from Pitcher Mt., showing that at this distance (two and one-half miles), adjacent terraces cannot be differentiated by the unaided eye. The scarp between the levels occurs at the point a, and can be seen by holding a straight edge parallel with the sky line in the left half of the picture.



- b. Sand plain at White Rock as seen from the floodplain of the Pawcatuck River on the west. The part to the south, between a-b is 20 feet higher than the rest of the deposit.

PLATE VII.

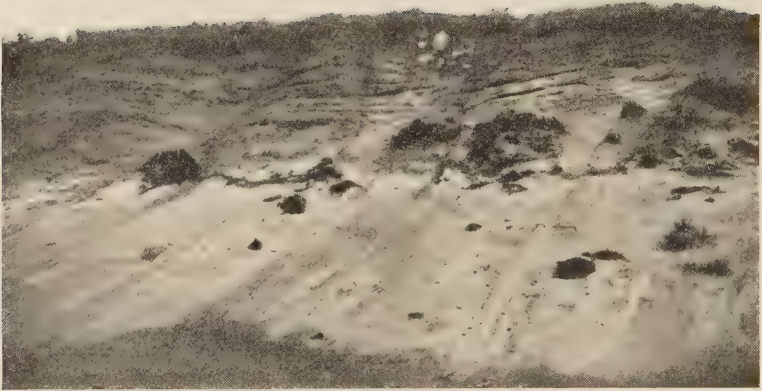


a. Near view of contact of coarse and fine beds in the finger-like projection of the sand plain southeast of White Rock, showing contortions probably due to the drag of icebergs.



b. Contact between Wisconsin till (upper right hand), and stratified sands and gravel below, in wave-cut cliff, Watch Hill, R. I.

PLATE VIII.



a. Valley cut in horizontal beds of banded till and crossbedded sands and filled with coarse drift, Watch Hill cliff.



b. Waterlaid gravels and sands overlain by till and showing peculiar contortions over boulders in an underlying bed of till.
Newhall's new quarry, Bradford, R. I.

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